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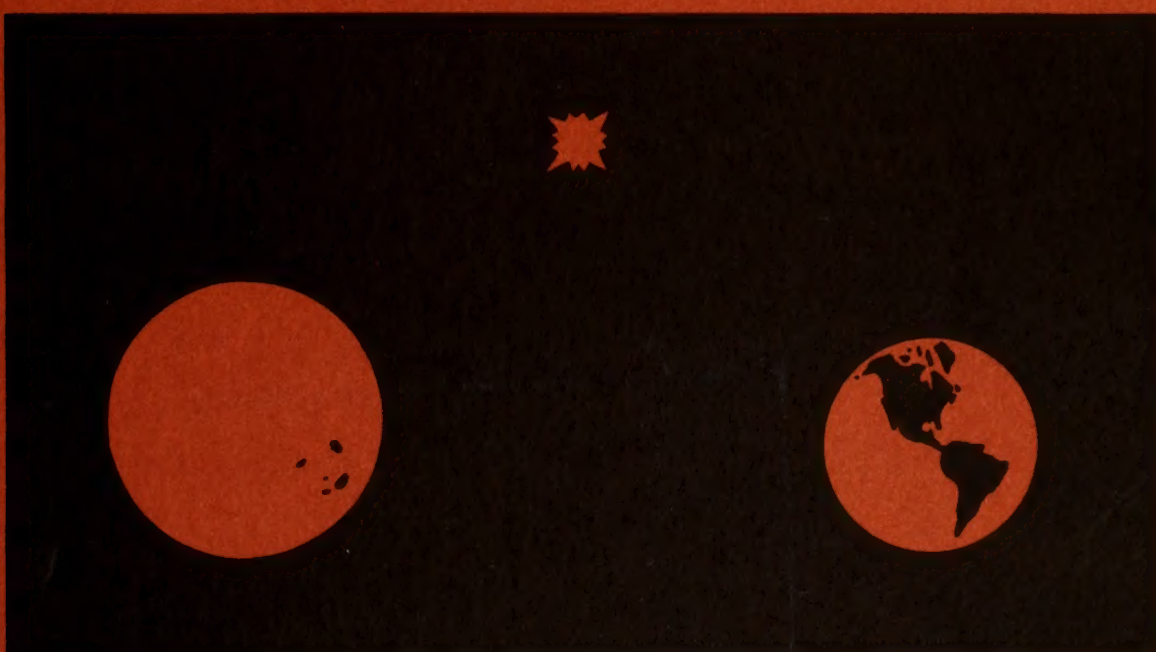

Cretaceous-Tertiary Extinctions and Possible Terrestrial and Extraterrestrial Causes

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CRETACEOUS-TERTIARY EXTINCTIONS AND POSSIBLE TERRESTRIAL AND EXTRATERRESTRIAL CAUSES

by the K-TEC* group

Proceedings of the workshop held in Ottawa, Canada

16 - 17 November 1976

Sponsored by the Paleobiology Division, National Museum of Natural Sciences (Canada) and by the Herzberg Institute of Astrophysics, National Research Council of Canada

*Pierre Béland, Paul Feldman, John Foster, David Jarzen, Geoffrey Norris, Kris Pirozynski, George Reid, Jean-René Roy, Dale Russell, Wallace Tucker.

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ACKNOWLEDGEMENTS

All participants in the K-TEC workshop wish to express their most sincere gratitude to the following persons: this volume is in its entirety an expression of the professional skills of Mrs. Gail Rice (Secretary, Paleobiology Division); Mrs. Heather Shannon (Executive Assistant, Museum of Natural Sciences) made arrangements for meeting accomodations and for excellent *in situ* meals, including a memorable evening dinner served by Mrs. Palisek and her staff at the Museum; Mr. Marcel Demers (Projectionist, National Museums of Canada) taped the proceedings, greatly facilitating the preparation of the Discussions.

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PREFACE

It is a source of considerable pleasure to me that the National Museum of Natural Sciences, with the collaboration and support of the Herzberg Institute of Astrophysics, was able to host the K-TEC workshop. Concerned, as it was, with an abrupt but unknown disturbance within the biosphere of our planet so many millions of years ago, it is anticipated that the workshop will lead to a better evaluation of current human environmental pressures. Indeed, an improved understanding of this ancient watershed in Earth history can only deepen our appreciation and respect for the natural biologic systems which grew from the debris of the age of reptiles and from which society now benefits in so many ways. It is interesting to note how greatly the record in the sedimentary basins of western Canada has contributed to our knowledge of planetary environments of that time. The Herzberg Institute joins me in expressing our gratitude to our colleagues from other institutions, for contributing their special insights to the discussions which we all enjoyed.

Louis Lemieux, Director
National Museum of Natural Sciences

The K-TEC workshop was convened for the purpose of defining avenues of research to resolve the long-standing problem of the extinctions terminating the dinosaurian era. The disciplines represented encompass the broadest range of scientific interests thus far assembled in this Museum for a single meeting. The proceedings of the workshop are herewith presented to the interested public in the hope that the workshop has been at least partly successful in attaining its objective. We further hope that the proceedings reflect the difficulties encountered in understanding exactly what transpired during one critical period in the distant past, and how tenuous the record is of an event which would probably have been very obvious to an observer of that time. One undisputed result of the workshop was, however, a profound respect for the fact that natural processes are seldom simple. A multidisciplinary orientation in Museum research can, therefore, be expected to produce valuable dividends in terms of public information and interest.

F. Hugh Schultz, Assistant Director
Operations and Research
National Museum of Natural Sciences

INTRODUCTION

Jean-René Roy and Dale Russell

Mankind is aware of the existence of many phenomena which are beyond its present understanding. Among these are the great extinctions in which the dinosaurs were eliminated, during the relatively brief transition between the Cretaceous and Tertiary Periods some 65 million years ago. The environmental changes which brought about these extinctions are of particular interest to this group, hence the derivation of the acronym K-TEC from Cretaceous*-Tertiary Environmental Change. Our interest is perhaps motivated by a latent fear of the recurrence of such major changes in the Earth's biosphere. Could the Earth undergo similar extinctions tomorrow? Could mankind trigger a chain of irreversible changes leading to biological catastrophy?

We have noted many difficulties and intrinsic contradictions in searching for plausible chains of terrestrial events which would lead to extinctions on the scale of those which occurred at the Cretaceous-Tertiary boundary. But the Earth occurs in a cosmic environment; its weather systems for example are powered from an extraterrestrial source, the Sun. Perhaps the Gordian Knot can be unraveled by seeking the culprit beyond the Earth.

Thus some justification exists for paleobiologists and space scientists to seek each others' assistance. Probing space and time on a cosmic scale appears extremely attractive as it leaves speculations unfettered by large bodies of established fact. Nevertheless even the scale of our wildest speculations is restricted by our limited point of view. The extinctions took place 6.5×10^7 years ago; our lifetime spans 6.5×10^1 years. Were we to journey to the uttermost ends of the Earth we could hardly be more than 6.5×10^{-10} parsecs from home (1 parsec = 3.26 light years = 3.0857×10^{18} cm). The biosphere is complex, amply challenging the intelligence and imagination of 10^5 - 10^6 individuals around the globe. Fewer than 10^3 individuals have concerned themselves with the fossil residues of organisms which were living

*The geological symbol for the Cretaceous is K in the vicinity of 6.5×10^7 years ago to the extent of writing papers about them. Yet there is little reason to suspect that planetary ecosystems were orders of magnitude simpler than today.

During the last 4×10^8 years, the biosphere has prospered over virtually the entire surface of the planet. The sedimentary record on both land and in the sea has been and continues to be profoundly affected by life processes. Thus if an extraterrestrial event did badly damage the biosphere, an unbalanced biosphere would in turn generate a series of changes in the sedimentary record. We would then be confronted with the extraordinarily confusing task of separating tertiary, secondary and primary effects of a single source of environmental stress. And the possibility of a catastrophy of strictly terrestrial origin cannot be excluded.

So it has been with both arrogance and humility that we have addressed ourselves to our task.

A total of ten oral presentations were made during the course of what we hope has been the first of a series of K-TEC workshops, held in Ottawa on November 16 and 17, 1976. These presentations have been developed further in the papers that follow, most of which have an annotated bibliography.

What does the paleontological record contain of that time 6.5×10^7 million years ago, which has perplexed so many paleobiologists? A summary synthesis of the paleontological data is attempted by Dale Russell, who concludes that a case can be made for a catastrophic extinction event at the end of Cretaceous time. Unfortunately, organisms react to a number of different stresses in the same way – by dying – and extrabiological evidence must be sought. Is there a mechanism by which dinosaurs could have become extinct through changes in the structure of terrestrial ecosystems? Pierre Béland notes that dinosaurian communities were generally similar to those of large African mammals, and explores the deleterious effects of large vertebrates upon vegetation. He concludes that the terminal Cretaceous environmental changes were too profound and too far-reaching to all be explained by terrestrial vertebrate-vegetation relationships.

Turning to the microfossil evidence, David Jarzen reviews the record of pollen from flowering plants across the Cretaceous-Tertiary boundary in North America. Extinctions on a generic and specific level did occur, but they were by no means as drastic as those which decimated the large reptiles, and there is no evidence of a sharp and enduring cooling at the time of the extinctions. In contrast Geoffrey Norris finds that the abundance of proximate cysts of marine planktonic algae, called dinoflagellates, is suggestive of a cooling of ocean waters in Alabama. He succinctly summarizes the detrimental effects of changes in sea levels and the carbon chemistry of the oceans to planetary environments on a global scale. Melanins serve to protect organisms from desiccation and harmful radiations. Kris Pirozynski notes that most fungi adapted to exposed environments contain unusual amounts of melanin, and that highly melanized spores of sac fungi are in turn unusually abundant in sediments of basal Tertiary age. These data should be considered in models which seek to account for the terminal Cretaceous extinctions.

The Earth's magnetosphere can change its polarity within less than a thousand years, and polarity reversals provide time horizons by which widely separated successions of sedimentary rock can be accurately compared. John Foster discusses these techniques, as well as the possible role of the Earth's magnetic field in climate, as a shield against extraterrestrial radiation and as an environmental parameter upon which terrestrial organisms depend.

We know the Sun as a source of energy and life. Its magnetic activity can produce complex interactions which trigger the most violent blast of energy within the solar system — the solar flare. The associated flash of UV radiation and X rays and the showers of energetic particles on Earth modify the structure and composition of our atmosphere. George Reid describes the physics and chemistry of the atmospheric changes induced by large particle events from the Sun (or from a nearby supernova), and examines some environmental consequences of the depletion of the ozone layer.

"Nothing changes under the Sun" must now be qualified. Our knowledge of the Sun is flawed by our inability to account for critical observations relating to solar processes. As summarized by Jean-René Roy, observational and theoretical limitations are not inconsistent with a 10% variation in solar luminosity over periods longer than 2 x 10^4years. Spectacular fluctuations of solar activity during the past few thousand years are discussed, as is the probability of solar flares one thousand times more energetic than the most powerful events so far observed.

Modern astrophysics describes a supernova as the explosion of a star which has exhausted its nuclear fuel; its core collapses under the force of gravity and the implosion suddenly liberates more energy than that available through thermonuclear processes. After describing the composition of normal cosmic radiation, Wallace Tucker uses the best available data to estimate the consequences of a supernova explosion occurring in the vicinity of the solar system, and presents observational and theoretical limits regarding the occurrence of a nearby supernova event.

Remnants of ancient supernovae can be identified in the galactic neighbourhood of the Sun by large rings of moving gas and magnetic fields, radiating X rays, light and radio waves. From radioastronomical and cosmochronological evidence Paul Feldman critically appraises the clues left behind by pulsars and supernova remnants.

Following the papers is a condensation of the discussions which took place during the meeting, arranged under five headings: the geosphere, the biosphere, the atmosphere and hydrosphere, the photic sphere, and the cosmosphere. These have been included because they contain material pertaining to the question of the extinctions which was less well developed within the individual presentations. It is regrettable that there were no participants present who could have commented in depth on factors relating to radiation biology, oceanic chemistry, and the environmental effects of volcanism. Hopefully these omissions will be filled in future workshops.

We conclude the proceedings by describing two scenarios presented in the form of flow diagrams of possible chains of events. These scenarios were prepared by P. Béland, Jean-René Roy and Dale Russell from the general ideas discussed during and after the K-TEC workshop. We are aware of the complexity of the problem and realize that some boxes of the diagrams hide complex sequences of non-linear interactions. Therefore, we present these scenarios as suggestions for areas of investigation and not as a summary of the workshop or of the papers contributed.

We believe that this workshop was an extremely fruitful experience. Each of us was obliged to communicate clearly with researchers in other fields who are also working on esoteric problems, and using methods which we were barely aware of. Because of this approach it was hardly possible to hide behind the protective barriers of a specialized jargon and methodology. We hope that the proceedings will convey something of our enthusiasm for this approach and prove the usefulness, if not the necessity, of such a strategy in studying environmental problems.

THE BIOTIC CRISIS AT THE END OF THE CRETACEOUS PERIOD

Dale A. Russell

There is a consensus among paleobiologists that the dinosaurs and other large reptiles typical of the Age of Reptiles became extinct about 6.5×10^7 years ago. It is also generally recognized that the great reptiles had been an integral part of planetary ecosystems for about 1.75×10^8 years preceeding their extinction, and that some other organisms vanished with them. The problem of their extinction therefore has an ecological dimension.

Paleobiologists have distributed themselves among proportionally about as many separate professions as have modern biologists. If one were to enquire of a student of ancient salamanders whether or not anything unusual happened about 6.5×10^7 years ago the response would truthfully be that his research clearly indicates "no." A student of dinosaurs would reply truthfully and emphatically "yes."

A generalist would accurately note that the fundamental continuity of life on our planet was not interrupted at this time, nor did any basic group of organisms (monerans, protists, plants, animals, fungi) become extinct. However, it has been convincingly demonstrated that on a family group level (e.g. Didelphidae - opossums, Tyrannosauridae - tyrannosaurs) "... a brief period of crisis [did occur which was] characterized by an abnormally high rate of extinction..." (Cutbill and Funnell 1967, p. 279).

It would seem that different groups of organisms responded differently to the crisis (Weidmann 1969, see Fig. 1), and that finer taxonomic resolution is accompanied by a greater apparent disturbance in continuity (Raup 1975, see Fig. 2). The utility of assembling groups of organisms into gross ecological units, and comparing their diversity before and after the crisis on a finer taxonomic level is therefore indicated.

The number of fossil genera (e.g. *Didelphis, Tyrannosaurus*) which are currently recognized as having lived in general proximity to the time of the

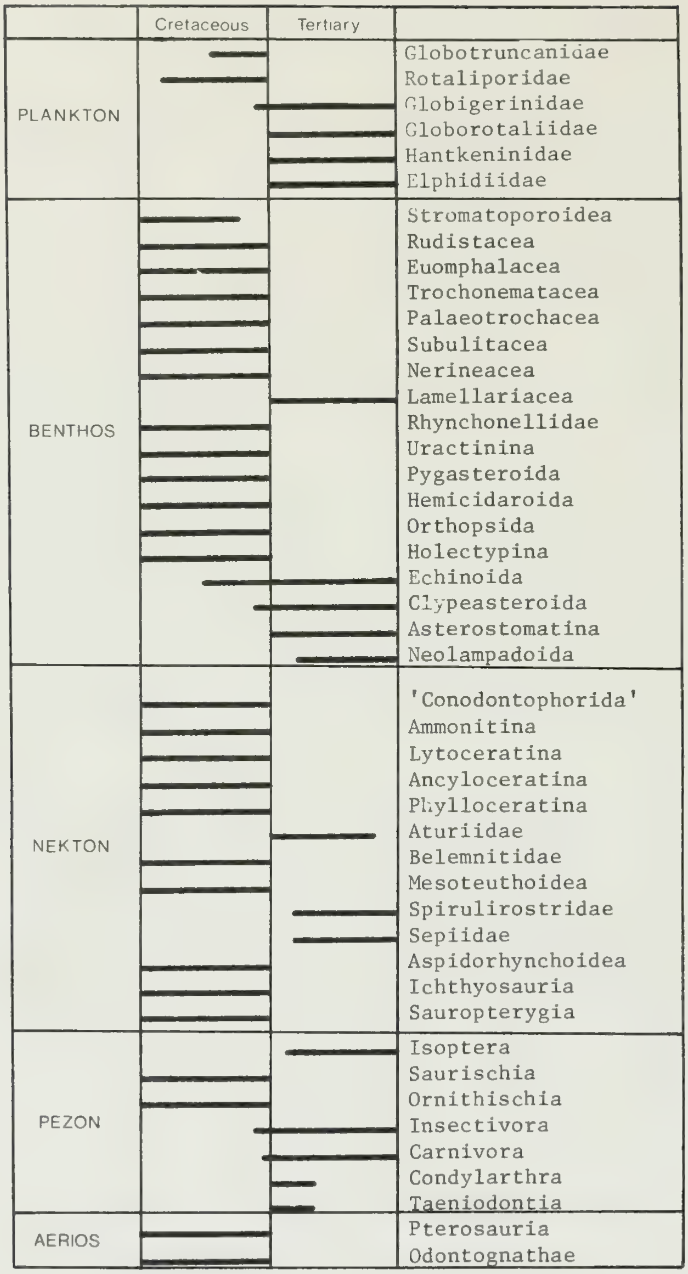


FIGURE 1. *Extinctions at the Cretaceous-Tertiary boundary, arranged in general ecologic groupings (after Weidmann 1969, with minor alterations).*

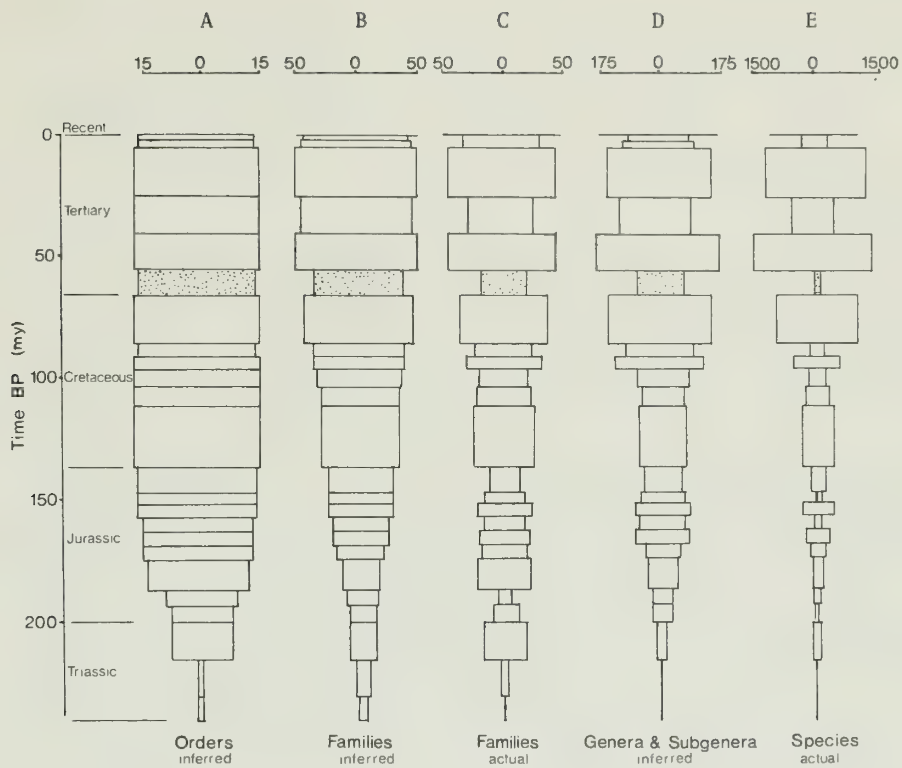


FIGURE 2. *Echinoid diversity during the past 250 million years, expressed at different taxonomic levels. Note the marked retrenchment at the Cretaceous-Tertiary boundary, which becomes increasingly apparent towards a species level of taxonomic resolution (after Raup 1975).*

TABLE I: *(For sources of reference, see following page).*

	Before Extinctions	After Extinctions	
FRESH WATER ORGANISMS			
Cartilaginous fishes	4	2	
Bony fishes	11	7	
Amphibians	9	10	
Reptiles	12	16	
	36	35	(97%)
TERRESTRIAL ORGANISMS			
(including fresh-water organisms)			
Higher plants	100	90	
Snails	16	18	
Bivalves	10	7	
Cartilaginous fishes	4	2	
Bony fishes	11	7	
Amphibians	9	10	
Reptiles	54	24	
Mammals	22	25	
	226	183	(81%)
FLOATING MARINE MICRO-ORGANISMS			
Acritarchs	28	10	
Coccoliths	43	4	
Dinoflagellates	57	43	
Diatoms	10	10	
Radiolarians	63	63	
Foraminifers	18	3	
Ostracods	79	40	
	298	173	(58%)
BOTTOM-DWELLING MARINE ORGANISMS			
Calcareous algae	41	35	
Sponges	261	81	
Foraminifers	95	93	
Corals	87	31	
Bryozoans	337	204	
Brachiopods	28	22	
Snails	300	150	
Bivalves	399	193	
Barnacles	32	24	
Malacostracans	69	52	
Sea lilies	100	30	
Echinoids	190	69	
Asteroids	37	28	
	1,976	1,012	(51%)
SWIMMING MARINE ORGANISMS			
Ammonites	34	0	
Nautiloids	10	7	
Belemnites	4	0	
Cartilaginous fishes	70	50	
Bony fishes	185	39	
Reptiles	29	3	
	332	99	(30%)
OVERALL	2,868	1,502	(52%)

TABLE I: *NUMBER OF GENERA OF FOSSIL ORGANISMS CURRENTLY RECOGNIZED AS HAVING LIVED PRIOR TO AND FOLLOWING THE TERMINAL CRETACEOUS EXTINCTIONS.*

Moore, R.C. [ed.] Treatise on invertebrate paleontology. Geol. Soc. Am.

This excellent encyclopedia summarizes existing information on the stratigraphic distribution of many fossil invertebrate genera. Volumes here consulted include: D (radiolarians), E (sponges), G (bryozoans), H (brachiopods), N (bivalves), L (ammonites), Q (ostracods), R (malacostracans and barnacles), T (sea lilies) and U (asteroids).

For other groups the following have been consulted:

Acritarchs -	*Tappan, H. and A.R. Loeblich. 1972. 24th Int. Geol. Congr. 7:205-213.*
Coccoliths -	*Ul Haq, B. 1973. Mar. Geol. 15:M25-M30; an average of three species per genus is taken from lists in Farinacci, A. 1969-1974. Catalogue of calcareous nannofossils, vols. 1-7. Rome.*
Dinoflagellates -	*See Harker and Sarjeant 1975.*
Diatoms -	*Estimate based on sustained family diversity levels in Hallam, W.B. et al. 1967. The Fossil Record. Geol. Soc. London.*
Calcareous algae -	*Poignant, A.F. 1974. Newsl. Stratigr. 3: 181-192. See Fig. 3.*
Higher plants -	*D.M. Jarzen, pers. comm. 1976.*
Foraminifers -	*Cushman, J.A. 1946. U.S. Geol. Surv. Prof. Paper 206; Ibid. 232.*
Corals -	*Newell, N.D. 1971. Am. Mus. Novit., No. 2465.*
Snails -	*Tozer, E.T. 1956. Geol. Surv. Can. Mem. 280; marine snails are assumed to be less diverse than bivalves and to have suffered a comparable decline.*
Nautiloids and belemnites -	*Newell, N.D. 1966. Proc. Acad. Nat. Sci. Philadelphia 118:63-89.*
Echinoids -	*See Raup 1975.*
Fishes -	*Romer, A.S. 1966. Vertebrate paleontology, 3rd ed. Univ. of Chicago Press. 468 p.*
Amphibians -	*Estes, R. 1975. Herpetologica 31:365-385, and references cited therein.*
Reptiles -	*Estes, R. 1970. Brev. Mus. Comp. Zool. No. 343; Russell, D.A. 1975. Geol. Assoc. Can., Spec. Pap. 13:119-136, and references cited therein.*
Mammals -	*Clemens, W.A. 1973. Univ. Calif. Publ. Geol. Sci. 94, and references cited therein.*

extinctions of 6.5 x 10^7 years ago has been calculated (Table I). In most cases they are from a period of time spanning the last 2 x 10^7 years of the Tertiary. In the case of marine microfossils and terrestrial organisms the interval is generally much closer to the extinction event, but in several groups of marine macro-fossils it is larger. The record of terrestrial organisms is here limited to North America; for marine organisms coverage is global, although existing information is more complete from North America and Europe.

This "sampling" minimizes the decline in generic diversity in that genera not recorded in strata which were deposited immediately after the extinctions, but because of their presence in older and younger strata must have been present then, are included. Neither is the high rate of generic turnover in some regions reflected in the figures. An interesting pattern is nonetheless suggested:

- there was an overall decline in generic diversity by about 50%;
- organisms living in fresh-water (streams, rivers, small lakes) were virtually unaffected by the extinctions;
- terrestrial organisms, with the exception of land-dwelling vertebrates, were little affected;
- where major groups of organisms inhabited both fresh-water and marine environments (bivalves, reptiles), those in the marine environment were more adversely affected;
- there was a wave of progressively more severe extinctions from lower to higher trophic levels, or in the direction of the larger consumers, in the world's oceans.

No terrestrial vertebrate heavier than about 25 kg is known to have survived the extinctions.

With the decline in generic diversity there was a concurrent decline in the number of species present in each genus. Thus in dinoflagellates (Harker and Sarjeant 1975, charts 8-26) an average of 1.86 species per genus have been identified in strata of terminal Cretaceous age, and an average of 1.26 species per genus in strata of basal Tertiary age. In echinoids (Raup 1975)

p. 16: extinctions of 6.5 x 10^7 years ago has been calculated (Table I). In most cases they are from a period of time spanning the last 2 x 10^7 years of the Cretaceous and the first 1 x 10^7 years of the Tertiary. In the ...

these ratios are respectively, 21.26 and 1.13. It is beyond the capacity of this paleobiologist to calculate a figure which would represent a global average, but intuitively a general decline in the number of species per genus of 50% does not seem unreasonable.

This being so, it would appear that about 75% of the species of organisms living on our planet during terminal Cretaceous time vanished at the beginning of the Tertiary.

An extinction of this scale would be extraordinary even if it took place over an interval of 5 x 10^7 years. However, chronologic evidence based on radioisotopic decay rates and evolutionary rates of floating marine foraminifers indicates that the extinctions took place within 2 x 10^6 years (see Van Hinte 1976). The biotic transformation represented by the extinctions greatly exceeds that resulting from the combined effects of continental glaciations and human invasions of North America during the last 2 x 10^6 years (Russell 1976).

A lower limit for the duration of the interval during which the extinctions took place has not yet been determined. In the most complete sedimentary successions where this interval has been identified it is simply represented as a bedding plane, suggesting a very short duration indeed (1-100 years?). John Foster and I, with the able and sympathetic assistance of Gilles Danis, have identified in rapidly-deposited deltaic sediments in Saskatchewan, a series of short-term geomagnetic events in close proximity to the Cretaceous-Tertiary boundary (see Foster paper). Using these as a very tight grid of time lines, we hope to obtain a better resolution of the duration of the extinctions on a world-wide basis. We are now in the process of analyzing paleomagnetic samples from Saskatchewan, Montana, Wyoming, Alabama, Denmark, France and New Zealand.

In our field work we have invariably noted a change in the pattern of sedimentation associated with the extinction horizon, where the latter has been identified. Often there was an increase in the kinetic energy of water from which the sediments were deposited, as well as colour changes suggestive of more intensive subaerial weathering and submarine erosion/solution phenomena. With the exception of preliminary works by Tappan (1968) and Worsley (1974) the sedimentary record at the time of the extinctions remains essentially unstudied.

It would appear, therefore, that the sum of paleobiological information at hand supports the hypothesis that a peculiar but profound extinction event took place at the Cretaceous-Tertiary erathem boundary. Although planetary — limited sources of biotic stress were almost certainly operative during this interval, available evidence does not favour a terrestrial mechanism over an extraterrestrial one as a primary agent leading to the production of the peculiar extinction and sedimentary phenomena described above.

REFERENCES

Cutbill, J.L. and B.M. Funnell. 1967. Numerical analysis of the fossil record, p. 791-820. *In* W.B. Harland [ed.] The Fossil Record, Geological Society, London.

The analysis appears in a very useful volume summarizing the distribution of organisms, generally on a family group level, through geologic time.

Harker, S.D. and W.A.S. Sarjeant. 1975. The stratigraphic distribution of organic-walled dinoflagellate cysts in the Cretaceous and Tertiary. Rev. Palaeobot. Palynol. 20(4):217-315.

A tabular synopsis of the temporal and geographic distribution of dinoflagellate species.

Hays, J.D. and W.C. Pitman III. 1973. Lithospheric plate motion, sea level changes and climatic and ecological consequences. Nature 246:18-22.

The terminal Cretaceous extinctions are linked to a regression of epicontinental seas in the wake of a reduction in sea floor spreading rates.

McAlester, A.L. 1970. Animal extinctions, oxygen consumption, and atmospheric history. J. Paleontol. 44(3):405-409.

Correlation is noted between oxygen consumption rates of living organisms, and the vulnerability of closely related forms to past mass-extinction events.

Newell, N.D. 1963. Crises in the history of life. Sci. Am. 208:76-92.

Groups of organisms are postulated to have gradually become extinct with the onset of unfavourable environmental conditions, often of planetary extent.

Raup, D.M. 1975. Taxonomic diversity estimation using rarefaction. Paleobiology 1(4):333-342.

Rarefaction techniques used to estimate the specific diversity of living organisms by sampling, when applied to the fossil record, demonstrate that echinoids have become more diverse through phanerozoic time. The greatest retrenchment in echinoid specific diversity occurs at the Cretaceous-Tertiary boundary.

Russell, D.A. 1975. L'extinction des sauropsidés à la fin de l'ère secondaire - une hypothèse. Colloq. Int. Cent. Natl. Rech. Sci. 218: 513-518.

Biostratigraphic phenomena associated with the Cretaceous-Tertiary boundary may have resulted from an environmental deterioration produced by a nearby supernova.

Russell, D.A. 1976. Mass extinctions of dinosaurs and mammals. Nat. Can. (Ottawa) 5(2):18-24.

Cretaceous-Tertiary vertebrate extinctions were much more severe than those accompanying the onset of the Ice Ages and the arrival of man in North America.

Sloan, R.E. 1969. Cretaceous and Paleocene terrestrial communities of western North America. Proc. N. Am. Paleontol. Convention, E: 427-453.

Biotic changes on land coinciding with the Cretaceous-Tertiary boundary are suggested to have proceeded in the north-to-south wave following the withdrawal of the interior sea.

Tappan, H. 1968. Primary productivity, isotopes, extinctions and the atmosphere. Palaeogeog. Palaeoclimatol. Palaeoecol. 4:187-210.

A crash in oceanic phytoplankton productivity brought about by decline in land-derived nutrients may have caused widespread exterminations among organisms dependent upon them for food, as well as an abrupt decline in atmospheric oxygen essential for the respiration of higher vertebrates. See also McAlester 1970.

Van Hinte, J.E. 1976. A Cretaceous time scale. Bull. Am. Assoc. Petrol. Geol. 60(4):498-516.

This is the most recent revision of the paleontologic and geochronologic time scales for the Cretaceous Period.

Weidmann, J. 1969. The heteromorphs and ammonoid extinction. Biol. Rev. 44: 563-602.

Ammonites did not acquire unusual "degenerate" shell morphologies

prior to their extinction. A causal relationship exists between the decline in ammonite diversity toward the end of the Cretaceous, and an increasing tempo of regressions of shallow, epicontinental seas.

Worsley, T. 1974. The Cretaceous-Tertiary boundary event in the ocean. Soc. Econ. Paleontol. Mineral., Spec. Publ. 20:94-125.

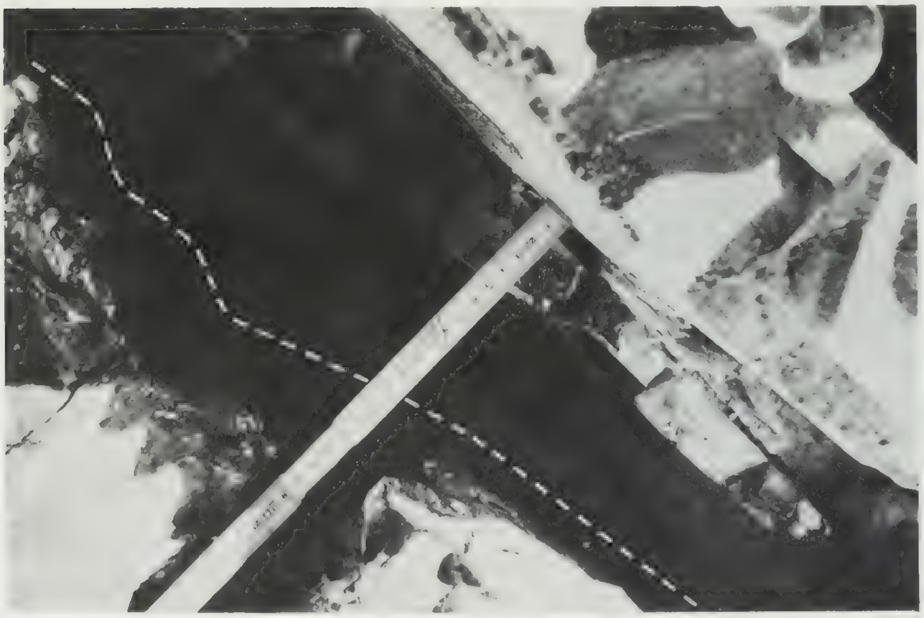
The marine phytoplankton crisis caused a general climatic deterioration and pelagic carbonate deposition to cease in ever-shallow depths over a 10^5 - 10^6 year interval until it finally ceased even in the photic zone at the end of Cretaceous time. See Norris paper.

FIGURE 3. *The Cretaceous-Tertiary boundary in Makoshika State Park, near Glendive, Montana, U.S.A. The arrow indicates the extinction horizon, as determined by palynofloral evidence (R.H. Tschudy, pers. com. 1972). An articulated forelimb of* Triceratops *sp. occurs 3.5 m below the extinction horizon at this locality. Below the arrow is the Hell Creek Formation, above is the Tullock Formation.*

FIGURE 4. *The Cretaceous-Tertiary boundary, as here postulated (dashed line) below the Barre du Cengle on the southern flank of Mt. St. Victoire, near Aix-en-Provence, France. The red shales below the dashed line contain fragments of dinosaur egg shells, the white ledge higher on the slope is the "calcaire formant toit" of Dughi and Sirugue (Bull. Soc. géol. Fr., 1968, 7, 10:542-548), and the crest of the hill is formed from the Poudingue de la Galante.*

FIGURE 5. *The Cretaceous-Tertiary boundary as exposed in the Middle Waipara River section (Laidmore Formation), South Island, New Zealand. Arrows indicate the boundary horizon at the upper limit of terminal Cretaceous guide fossils (Percy Strong pers. com. 1976). Dr. Malcolm Laird, of the New Zealand Geological Survey is standing in the foreground.*

FIGURE 6. *The Cretaceous-Tertiary boundary (dashed line) as exposed on Woodside Creek (Mead Hill Formation), near Ward, South Island, New Zealand, established on the basis of foraminiferal guide fossils (Percy Strong, pers. com. 1976). The dashed line defines the upper limit of Cretaceous limestones; immediately above is an ochrous band of clays grading upward into a series of increasingly thick, undulating siliceous strata.*



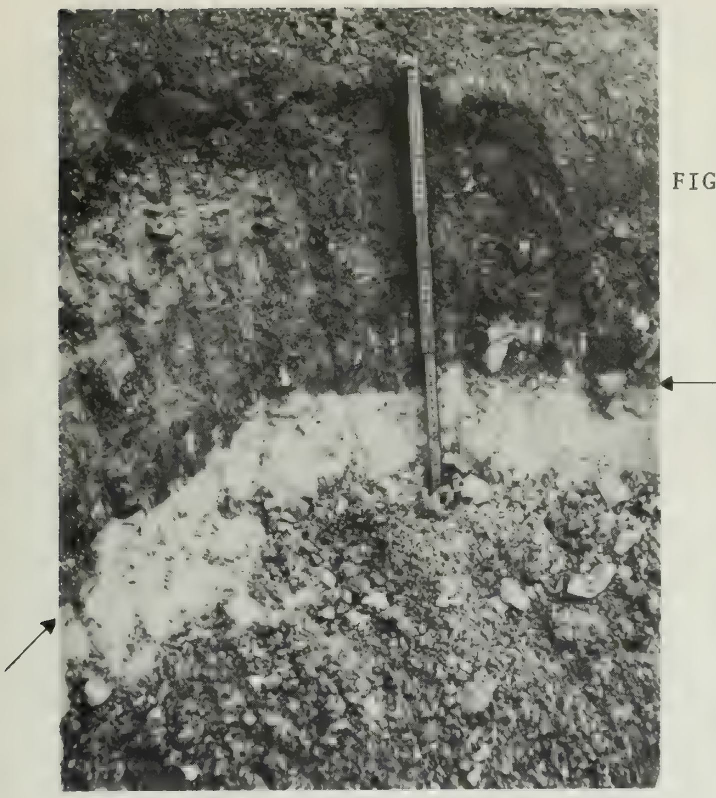


FIGURE 7. *The Cretaceous-Tertiary boundary (between arrows) on an abandoned, post-glacial sea cliff at Kølby Gård near Hunstrup, Jutland, Denmark. Semi-lithified fragments of the latest Cretaceous White Chalk were broken away and redeposited within gray-green marls (Fish Clay equivalent) of earliest Tertiary age at the base of the Bryozoan Limestone.*

FIGURE 8. *The Cretaceous-Tertiary boundary (between arrows) along highway 7 south of Braggs, Alabama. Below the extinction horizon are shallow-water marine marls of the Prairie Bluff Formation; above are marine marls and limey sand ledges belonging to the Clayton Formation.*

MODELS FOR THE COLLAPSE OF TERRESTRIAL COMMUNITIES OF LARGE VERTEBRATES

Pierre Béland

The most diverse dinosaurian assemblage ever found comes from the Judith River Formation of Alberta. This fauna lived in a tropical or subtropical scene of flood plains about 10 million years before the end of the Cretaceous. Indirect evidence indicates that although faunal replacements occurred later on, no significant decrease in diversity took place before the end of the period (Russell 1975).

A complex array of highly evolved forms occupied all major vertebrate niches that are today filled by mammals and birds. The traditional view of dinosaurs as ill-adapted mere stepping-stones in the evolution of higher forms is untenable. Dinosaurs were then the dominant herbivores and carnivores of a rich and complex world with a quite modern-like flora (see Jarzen paper). In fact, the more evolved dinosaurs had brains approaching in size modern mammals and birds (Russell 1972). Certainly, no contemporaneous vertebrate groups were then as evolved and diversified.

There have been attempts to explain the disappearance of the dinosaurs as the result of a competitive event with mammals. Actually, the subsequent success of mammals and birds is more easily explained through the removal of dinosaurs than vice-versa. The graphs in Fig. 1 and Fig. 2 suggest that the main radiations of birds and mammals occurred after, and as a response to, the void created by the disappearance of the dinosaurs. The response of birds was quite rapid, particularly among land birds where diversification had begun earlier. However, these usually do not preserve well, and bias is probable. Mammals took a longer time to reach maximum diversity, but the increase was rather sudden after the end of the Cretaceous.

The main problem therefore is to find a mechanism that created such a void, thus allowing further diversification. I wish to explore some alternatives to extraterrestrial events and to determine whether they are plausible. Some explanations gravitate around an alleged change in the flora near the end of

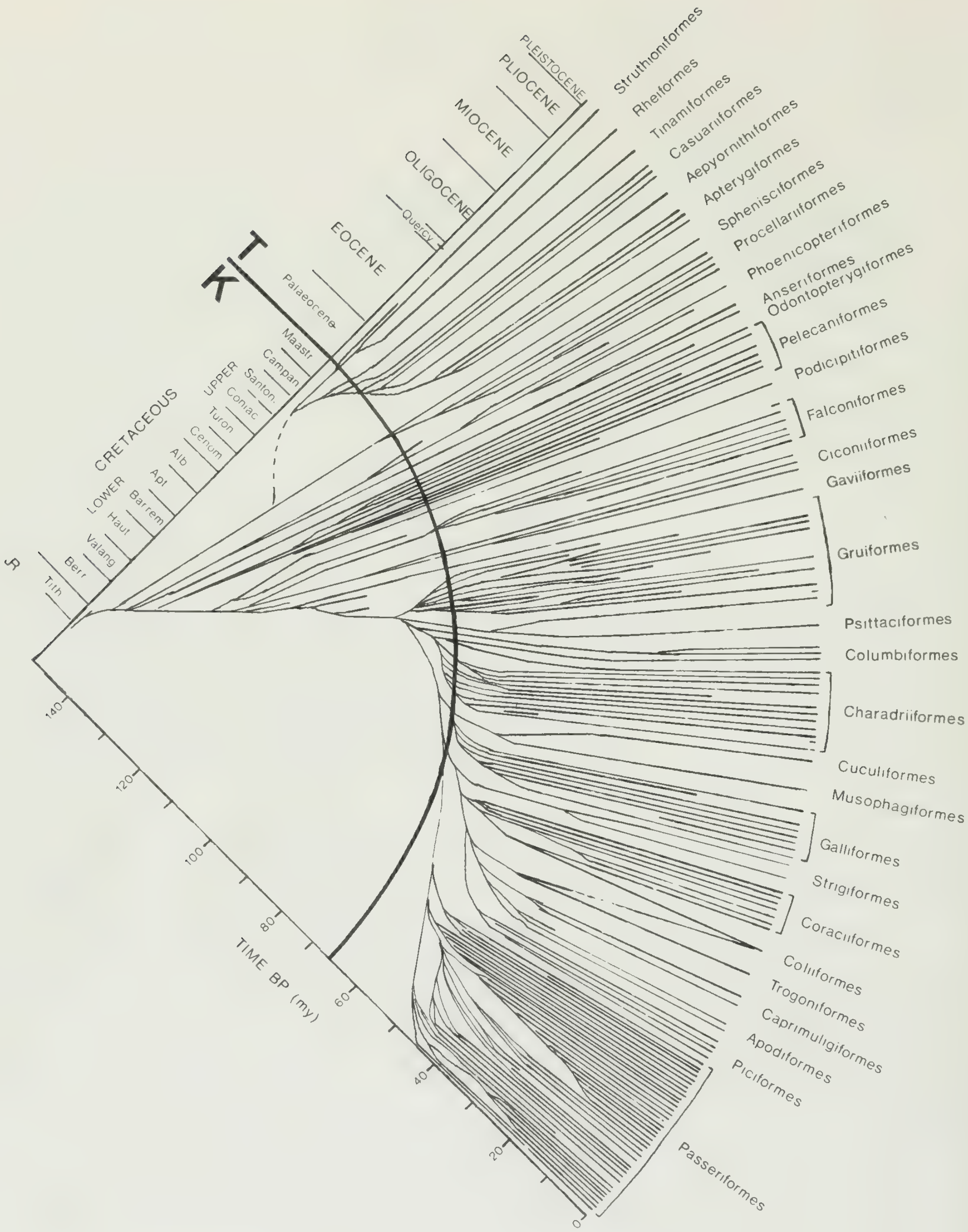


FIGURE 1. *The families of birds (thin lines, grouped into orders) through geologic time. There are 46 families at the Cretaceous-Tertiary boundary (marked as a heavy arc), but 84 at the beginning of the Eocene, approximately 10 million years later (redrawn from Fisher 1967).*

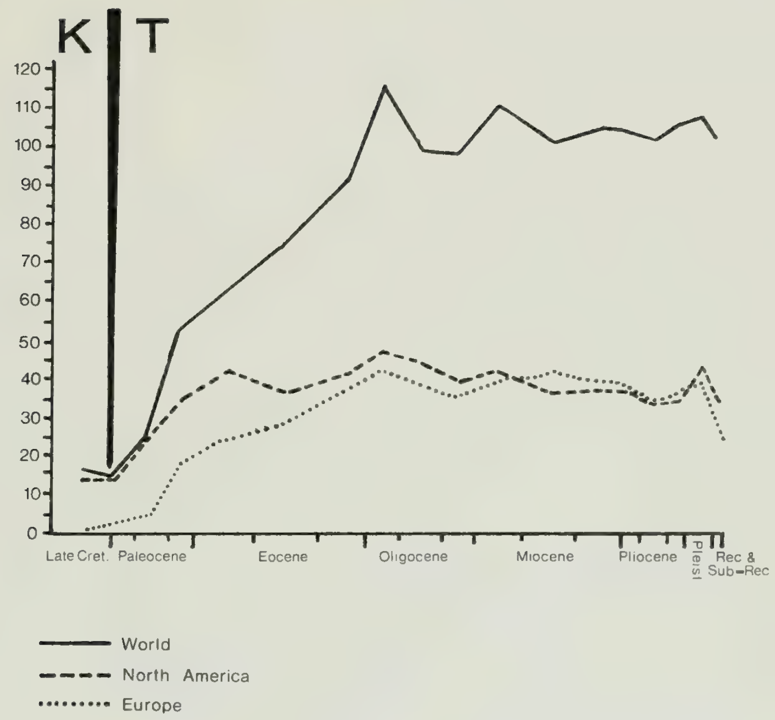


FIGURE 2. *The families of mammals near the Cretaceous-Tertiary boundary and to the present (bats and mysticete plus odontocete whales are excluded). Graphed are data from those continents where the record is continuous through the boundary, as well as cumulative data for the whole world (redrawn from Lillegraven 1972).*

the Cretaceous. Thus, Swain (1974) suggested that dinosaurs had to switch to a diet of flowering plants, some of them containing poisonous alkaloids. This theory assumes that dinosaurs could not discriminate between plants that coevolved with them. It assumes also that the angiosperms appeared quite suddenly at the very end of the Cretaceous. Both are very doubtful. And, in the Western Interior of North America, the case for a drastic floristic change at the boundary is thin (see Jarzen paper).

It has been suggested that the very diverse dinosaurian communities were the result of long-term evolution in a stable system, as stated by the theory of diversity-stability relationships in ecology. However, recent theoretical work has shown that there is no simple relationship between diversity and stability in ecological systems. Indeed, some results in analytical mathematics hint that complexity should decrease stability (see Goodman 1975). Many argue for a climatic change that directly, or indirectly through side effects, caused the dinosaurian extinctions (see for example Anonymous 1975). As mentioned above, there is no evidence for such a sharp change, based on studies of terrestrial vegetation. These theories assume that the very large diversity of vertebrates formed in warm equable climatic conditions were no longer viable when the warm climatic belt moved southwards. However, a decrease in diversity of large vertebrates is not a necessary result of a latitudinal shift. Fleming (1973) looked at forest communities of mammals of North and Central America, and analyzed the observed latitudinal changes in species diversity, ecological diversity and community structure. He found that these are primarily a result of a southward increase in the numbers of bat species, the majority of which feed on tropical fruits and flowers.

The Pleistocene mammal faunas of unglaciated Yukon and Alaska demonstrate that complex communities of large vertebrates can exist in cold climates. Undoubtedly, the early Tertiary was much warmer than Beringia. It is still controversial whether dinosaurs were endothermic (with a high metabolism) or ectothermic (cold-blooded) (Bakker 1972, Dodson 1974). Certainly, provided that the average climate is warm, large animals do not need special physiological mechanisms for regulating their body temperature, even with diurnal fluctuations in their environment (Spotila et al. 1973). Also, behavioural adaptations can compensate for the lack of anatomical adaptations. Apparently, homeothermy in large animals is not an essential attribute of mammals. African elephants, which range from hot arid grasslands to cold mountain plateaus are not strictly homeothermic (Elder and Rodgers 1975).

Furthermore, there are good indications that dinosaurian communities were not different from fossil mammalian communities so far as energy budgets are concerned (Bakker 1972). Current investigations in the Paleobiology Division of NMNS also show that the herbivore-carnivore ratio in the Judith River fauna is of the same order as that in extant large African mammal communities.

The foregoing demonstrates that the climatic change necessary to eliminate the dinosaurian communities is far in excess of what is documented by the fossil record. I now wish to discuss a process of faunal change that involves the structure, function and evolution of ecosystems dominated by large vertebrate communities living on Earth, the large mammals of East Africa. Is there a natural process by which they could change drastically, or even disappear, within a short period of time and without a strong climatic change?

There has been at several times in the geological record a trend towards large size in herbivores (and a corresponding increase in predator sizes). The main asset of large body size is a reduced energy expenditure per kg of body weight. Also, herbivores thereby avoid smaller predators, and in some cases become almost free from predation. This was probably the case with Jurassic brontosaurs and Pleistocene mammoths and is true for adults of African elephant, giraffe, rhino and to a lesser degree eland and buffalo. These large herbivores, because of sheer size, have very marked direct and indirect effects on vegetation: amount of food ingested, accessory damage to plants (breakage, trampling), soil compaction and trail erosion (decreasing penetration of rain and favouring run-off), etc. When large populations are involved, these effects can be dramatic.

In Africa, recent work has shown that populations of elephants can have a determining effect on vegetation. In certain areas, elephants are the main agent for destroying and preventing regeneration of woody vegetation to the benefit of grassland. Furthermore, they can even displace from these grasslands grazers that are more efficient energy transformers (Petrides and Swank 1965, Laws et al. 1975). It has been said that overexploitation of the habitat by elephants is the result of artificial (human) displacement of a previous equilibrium between elephants and forest (Laws et al. 1975). However, Naylor et al. (1973) have good evidence that "there is no attainable natural equilibrium between elephants and forests." The relationship has a cyclical pattern, with elephant numbers eventually dwindling when destruction passes a threshold, to increase again when forest has regenerated. They do not think that in their study area (Luangwa Valley, Zambia) destruction will reach a point of no return. Are there conditions under which destruction of, initially, forest vegetation by large herbivores leads to a new permanent stage of open vegetation (grassland-type) maintained by fire, erosion and herbivores? Can this change occur quite rapidly and without a significant climatic change?

I suggest the following scenario. Imagine an area with a relatively moist climate, supporting woodland and forest vegetation interspersed with some patches of open areas. In the latter, a "grassland"-type of vegetation is dominant, with opportunistic heliotropic plants that regenerate well after fire or grazing. In this habitat, one, or possibly more species of large unspecialized herbivores are undergoing population growth. They exert increasing pressure on the denser patches of vegetation. If a short-term decrease in rainfall occurs (but not a definite change in temperature or long-term climatic regime) herbivores would concentrate in wetter areas and start destroying woodland and forest. This has the effect of opening up more areas for grassland vegetation, much faster than long-term climatic changes. Simultaneously, faunal effects favour increased erosion, while an increase in open areas favours both erosion and propagation of fire. In the long run, browsers would be displaced by grazers. Finally, grazing animals would contribute to the maintenance of grassland, erosion and fire propagation.

Several of these interactions are catalytic and help to speed up the process, as summarized in Fig. 3. When extended over a period of time this could lead to drastic change in vegetation and erosional patterns, and to faunal replacements.

To see whether this process could have happened in the past, I have reviewed some paleovertebrate faunas. The process seems to explain some faunal changes in the Great Basin of North America in the Miocene-Pliocene. There, the replacement of woodland by grassland is attributed to a gradual decrease in rainfall (Shotwell 1961). However, it occurred without a significant reduction in aquatic habitats, which should result from increased aridity. In the Pleistocene, the process might explain the rates of expansion and subsequent collapse of the arctic steppe biome in Yukon and Alaska (see Matthews 1976). In this case, the triggering mechanism could have been a lowering of sea levels and subsequent drying of climate.

The dinosaur fauna of the Judith River Formation contains many more large taxa than any other fossil or extant vertebrate community. The amount of plant material ingested by the herbivorous forms must have been very impressive. There was opportunity for extensive damage to the vegetation, following unusual build-up in the population numbers. According to the process outlined above, there could occur a physiognomic change in the vegetation, without a marked floristic change, as seen in the fossil record. This would also lead to a corresponding change in herbivorous taxa of dinosaurs, towards the Cretaceous-Tertiary boundary.

Can the above process lead to a total collapse of the large vertebrate communities? It seems to better explain faunal replacements rather than extinctions, where the effect of the large herbivores is to remove forest to the benefit of grassland. However, some areas cleared by elephants are taken over by unproductive and unpalatable bushes. These cannot support a complex fauna of grazers, and, were they to cover extensive areas, a sharp decrease in faunal diversity would occur. Certainly, it is possible that at some point through this evolutionary process, ecosystems become very vulnerable to a

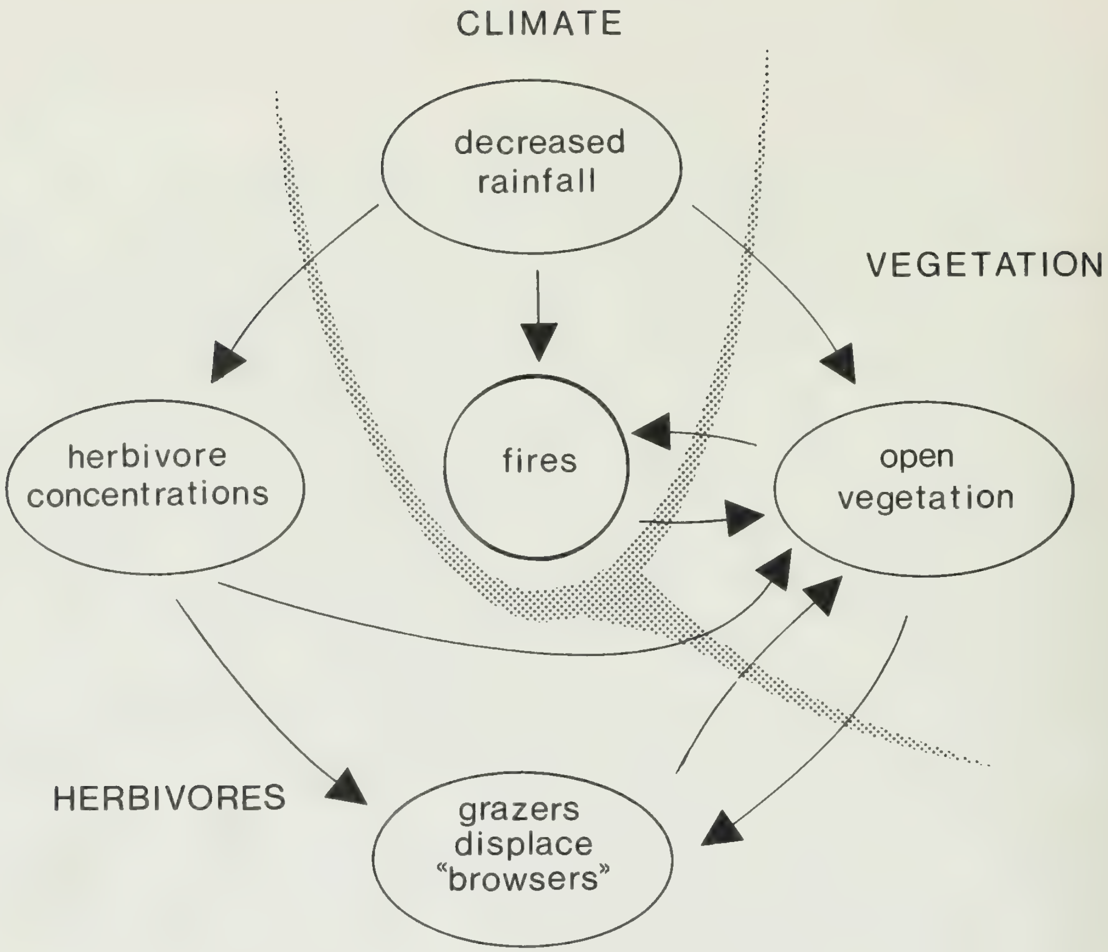


FIGURE 3. *Simplified model of the relationships between climate, vegetation and large herbivores. Some of the interactions shown are catalytic and would accelerate an opening and degradation of the vegetation, following a slight displacement of the equilibrium with climate.*

slight climatic change. Yet, it must be remembered that the faunal extinction that occurred at the close of the last glacial age was less pronounced than that which occurred at the end of the Cretaceous (see Russell paper). More dramatic mechanisms must be sought.

The environmental changes in the biosphere at the K-T boundary were profound. Studies of terrestrial vertebrate communities may help to explain some local and progressive changes, such as replacement of large vertebrate faunas, changes in vegetation structure without replacement of floras, increased deposition rates due to greater opportunity for erosion without changes in climate and rainfall. However, other changes may require other explanations. And the simultaneous occurence of all the changes may require more universal and catastrophic causes. Although some environmental changes can be explained through intrinsic "natural" causes, these are not always the only possibility. Thus, the natural succession stages toward climax in a community can be reversed by overgrazing (a "natural" model outlined in this paper), but also by introduction of toxic materials or by gamma irradiation (Whittaker and Woodwell 1971).

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Adam, J.-G. and P. Jaeger. 1976. Suppression de la floraison consécutive à la suppression des feux dans les savanes et prairies de la Guinée. C.R. Hebd. Séances Acad. Sci. Ser. D Sci. Nat. 282:637-639.

Fire is determining for flowering of grasses in African savannah and grassland.

Alexander, R. McN. 1976. Estimates of speeds of dinosaurs. Nature 261(5556): 129-130.

Measurements from a small sample of dinosaur tracks indicate that the majority of large dinosaurs preferred to walk...see Russell and Béland.

Anonymous, 1975. Did the anaerobes defeat the dinosaurs? New Sci. 68(977): 512.

The Deep Sea Drilling Project has extracted from the South Atlantic cores extremely rich in hydrocarbons and carbon, indicating that tremendous amounts of organic matter decayed under anaerobic conditions. This would have locked up huge quantities of C at the expense of atmospheric CO_2 and would have altered the Earth's albedo.

Bakker, R.T. 1972. Anatomical and ecological evidence of endothermy in dinosaurs. Nature 238:81-85.

Erect gait allowing more active locomotion, respiratory and circulatory mechanisms and bone histology are presented as anatomical evidence that dinosaurs had high metabolism. Ecological evidence comes from energy budgets and predator-prey ratios, found to be equivalent for dinosaur communities (three in Cretaceous, one in Jurassic) and mammal communities (two in Tertiary). See Dodson 1974.

Dodds, D.G. and D.R. Patton. 1968. Wildlife and land-use surveys of the Luangwa Valley, Zambia. FAO, Rome. 176 p.

Of interest here in this extensive management plan is the recommendation that large numbers of elephants and hippos be cropped from the Luangwa Valley. This, coupled with measures to stop erosion in the catchment area, would prevent further degradation of the vegetation.

Dodson, P. 1974. Dinosaurs as dinosaurs. Evolution 28(3):494-497.

A review of various physiological and anatomical clues to dinosaurian metabolism, in the ectotherm-endotherm controversy.

Elder, W.H. and O.H. Rodgers. 1975. Body temperatures in the African elephant as related to ambient temperature. Mammalia 39(3):395-399.

Body temperatures of male elephants vary between 32.5 and 37.5°C, and there is a linear relationship between body and ambient temperatures ($p<.001$).

Fisher, J. 1967. Fossil birds and their adaptive radiation, p. 153-154. *In* W.B. Harland [ed.] The Fossil Record. Geol. Soc., London.

A history of systematics of fossil birds and a discussion of their stratigraphical succession in the Mesozoic and Cenozoic.

Fleming, T.H. 1973. Numbers of mammal species in North and Central American forest communities. Ecology 54(3):555-563.

Seven habitats from tundra to rain forest are examined and compared with respect to the numbers and kinds of species in each, and to their size, spatial and trophic relationships. Latitudinal differences are accounted for by bats. Year-round availability of food, rather than spatial heterogeneity, is responsible.

Glover, P.E. 1968. The role of fire and other influences on the savannah habitat, with suggestions for further research. East Afr. Wildl. J. 6:131-137.

Savannah is defined and the roles of fire, grazing and human interference in the savannah habitat are discussed.

Goodman, D. 1975. The theory of diversity-stability relationships in ecology. Quart. Rev. Biol. 50(3):237-266.

The view that complex natural communities are more stable than simple ones was given formal expression about twenty years ago. This hypothesis developed over the years and theoretical models at first yielded gratifying results. Explanations were suggested, but all models suffered from questionable analogies and unrealistic mathematical representations. The paper evaluates attempts to support or refute the hypothesis and concludes that there is no simple relationship between diversity and stability in ecological systems.

Lamprey, H.F. 1963. Ecological separation of the large mammal species in the Tarangire game reserve, Tanganyika. East Afr. Wildl. J. 1:63-92.

Several species of ungulates can survive in the same habitat through a) occupation of different vegetation types, b) food selection, c) seasonal movements, d) feeding levels. There is a grazing succession whereby selection of one food type by each species makes another food type more readily available to the next species.

Laws, R.M., I.S.C. Parker and R.C.B. Johnstone. 1975. Elephants and their habitats. The ecology of elephants in North Bunyoro, Uganda. Clarendon Pr., Oxford. 376 p.

A good but very expensive treatise on African elephant ecology: history, environments, population dynamics, social organization, nutrition and a glimpse at effects on vegetation changes. Although several areas are cited, the book deals with the elephant problem in North Bunyoro, Uganda. Elephants are found to be much more important than fire in suppressing regeneration of woody vegetation and promoting grassland. This destructive action results from overcrowding of elephants in previously poorly used habitats, due to human demand for land in former elephant range. But see Naylor *et al.* 1973.

Lillegraven, J.A. 1972. Ordinal and familial diversity of Cenozoic mammals. Taxon 21(2/3):261-274.

Data on mammalian diversity are graphed for the world. All-time maxima were reached in Eocene-Oligocene (excluding bats and whales). No relationship was found between total diversity and continent size, but correlations are found between times of appearance of many mammalian and angiospermous orders. The dramatic taxonomic changes of the early Oligocene correlate well with a general deterioration of the world's climate.

Matthews, J.V. 1976. Arctic steppe - an extinct biome. Abstract, 4th bienn. meet., Amer. Quatern. Assoc., Tempe, Arizona' 9-10 October 1976.

(To be published?) Discussion on arctic grassland ecosystem in unglaciated Pleistocene Alaska-Yukon. The northern forest barrier was removed, allowing the central Asian grassland biome to move through Beringia to North America; an abrupt decline of the biome was marked by increase in abundance of shrub birch 12,000 to 14,000 years ago. The steppe fauna is to be best understood by comparison to other grassland ecosystems, as it is distinct from arctic tundra where ungulates are unimportant.

Naylor, J.N., G.J. Caughley, N.D.J. Abel and O. Liberg. 1973. Game management and habitat manipulation project, Zambia. FAO, Rome. 259 p.

Due to overstocking, forage is overutilized by elephant and hippo in the Luangwa Valley. Investigations into the effect of low hippo density have not shown the expected improvement on a riverine grazing area. Throughout the parks, there is a progressive reduction in forest cover, caused by elephants and fire. Elephant numbers are thought to vary cyclically, and a natural stable state with vegetation is unlikely. Therefore, the present situation would not be due to disturbance of a previous equilibrium. It is not thought that the downward trend will reach the stage at which it becomes irreversible.

Petrides, G.A. and Swank, W.G. 1965. Estimating the productivity and energy relations of an African elephant population. Proc. Int. Grassld. Congr. 9:831-842.

The elephant is a poor utilizer of food and, compared with other animals, has a lower growth rate per unit of food consumed.

Russell, D.A. 1972. Ostrich dinosaurs from the Late Cretaceous of Western Canada. Can. J. Earth Sci. 9(4):375-402.

A family (Ornithomimidae) is defined on the basis of skeletal morphology of three genera. The general body form parallels that of ratites; these dinosaurs had enormous eyes, relatively highly evolved brains and were extremely fleet.

Russell, D.A. 1975. Reptilian diversity and the Cretaceous-Tertiary transition in North America. Geol. Assoc. Can. Spec. Pap. No. 13: 119-136.

Late Cretaceous reptiles in central USA - Canada were as diversified as are mammals in same area today. The apparent climax in diversity during Campanian (10 to 5 million years before K-T boundary) and decline nearer the boundary is due to sampling bias. Extinctions at boundary are simultaneous in continental and marine facies. Reptilian diversity at beginning of Tertiary is markedly decreased.

Russell, D.A. and P. Béland. 1976. Running dinosaurs. Nature 264:486.

An 11 ton (comparable to two bull African elephants) herbivorous dinosaur was running at 27 km/hr. See Alexander 1976.

Shotwell, J.A. 1961. Late Tertiary biogeography of horses in the northern Great Basin. J. Paleontol. 35(1):203-217.

During the Miocene-Pliocene, savannah followed by grassland replaced woodland-forest in the northern Great Basin. Based on floral evidence, a decline in rainfall is hypothesized. The replacement of browsing horses by grazing horses coincides with these changes.

Spotila, J.R., P.W. Lommen, G.S. Bakken and D.M. Gates. 1973. A mathematical model for body temperatures of large reptiles: implications for dinosaur ecology. Am. Nat. 107(955):391-404.

Heat conduction models show that a large cylindrical reptile would have a relatively constant body temperature when exposed to warm diurnally fluctuating conditions, quite irrespective of metabolic rate. Gigantism is a useful strategy for poikilotherms in a stable warm climate, but decreased equability of climate would cause thermal stress.

Swain, T. 1974. Cold-blooded murder in the Cretaceous. Spectrum 120:10-12.

While ferns and conifers had no chemical deterrent for herbivores, flowering plants produced poisonous alkaloids. These are taken in larger quantities by turtles (who do not detect them) than by mammals. Swain concludes that dinosaurs therefore poisoned themselves. - Flaws are that alkaloid-bearing plants appeared 60 million years before the extinctions, and that the extinctions were sudden, not gradual. See text.

Whittaker, R.H. and G.M. Woodwell. 1971. Evolution of natural communities, p. 137-159. *In* J.A. Wiens [ed.] Ecosystem Structure and Function, Proc. 31st Ann. Biol. Coll., Oregon Univ. Press, Eugene.

Community evolution is examined with regards to diversity, pattern, physiognomy, succession and climax, productivity and biomass, and nutrient cycling. These characteristics evolve with time, as species within the community interact and become co-adapted. Thus, as the number of species (diversity) increases, they evolve toward diversity of distributions and attain individuality (community patterns), and a given community structure (physiognomy) is attained. Several physiognomic gradients may follow each other (succession and climax) with differences in productivity, biomass and nutrient cycles.

ANGIOSPERM POLLEN AS INDICATORS OF CRETACEOUS-TERTIARY ENVIRONMENTS

David M. Jarzen

Within the past two decades, pollen and spore analysis of rock samples of varying ages, lithologies, and geographic distribution, has taken its place along with paleobotanical studies of megafossils, in the interpretation of ancient vegetational cover and environmental interpretations.

The study of fossil pollen and spores owes its success in a large part to the facts that, (1) these microfossils were produced (by living plants) in great abundance, (2) they are very resistent to atmospheric and chemical degradation, and (3) they are easily preserved and recovered from most sedimentary rock types.

Palynological investigations have been carried out on sediments as old as the Precambrian (Barghoorn and Tyler 1963) all the way through the geologic column to the recent. Palynological studies presently underway at the National Museums of Canada are concerned with the evolution and biogeography of the flowering plants (angiospermae) during a time interval spanning the late Cretaceous (90 million years ago) and early Tertiary (30 million years ago). Since the angiosperms are primarily terrestrial plants, their pollen will be incorporated in sediments along with the pollen and spores of other land plants as gymnosperms (conifers and their kin) ferns and fern allies, and such lower plants as mosses, liverworts and others. Although all these forms must be considered when deriving paleoecological information, primary emphasis is here placed on the angiosperms.

Emphasis on the angiosperms is logical since it was during the Upper Cretaceous and Lower Tertiary periods that this group evolved, diversified and became the dominant form of terrestrial plant cover on the Earth. Equally as important is the fact that angiosperms are often sensitive environmental indicators. The works of Axelrod and Bailey (1969), Dilcher (1973), and Graham and Jarzen (1969) will illustrate this last point.

A fine source of easily available material with which to study the evolution and biogeography of early angiosperm plants is present in the extensive cover of sedimentary rocks of Cretaceous and Tertiary age in the Western Interior of North America. Previous studies of much worth in describing the nature of the pollen and spore floras from this region are: Stanley (1965), Norton and Hall (1969), Leffingwell (1971), Jarzen (1973), Awai-Thorne (1972), Srivastava (1970), Snead (1969), Tschudy (1971), and others.

Now being investigated is a section of sedimentary rocks which spans the Cretaceous-Tertiary transition. This section, the Morgan Creek section in southern Saskatchewan, Canada (Fig. 1) was sampled for paleomagnetic studies by D.A. Russell and G. Danis. The samples used for paleomagnetic analysis were later processed for their contained pollen and spores and are presently being investigated. The Morgan Creek section because of its extent (over 12 m) and sample coverage (over 200 samples at 10-15 cm intervals) is being used as a "type" pollen section with which other sections will be compared or contrasted. Eventually a more or less worldwide picture of angiosperm floras will emerge which will provide paleobiologists with data relevant to floristic changes, ecosystem structure and evolutionary trends within this very important group of plants.

Areas from which additional material has been collected include several localities in western Canada, Montana, North Dakota, Wyoming, Alabama (see paper by Norris), France, Denmark and New Zealand.

To recover and describe the pollen and spores contained within a fossil assemblage is but half the battle in elucidating paleoecological conditions of the past. The fossil material must be carefully compared, using optical and electron microscopy, with the pollen and spores of extant plants. Once these comparisons are carried out, much information of varying degrees of confidence is possible. This information can include temperature, seasonality, relief of the land, pH, comparable present-day geographic analogues, food supply, rainfall, plant migrations, and tectonic activity. (See for example

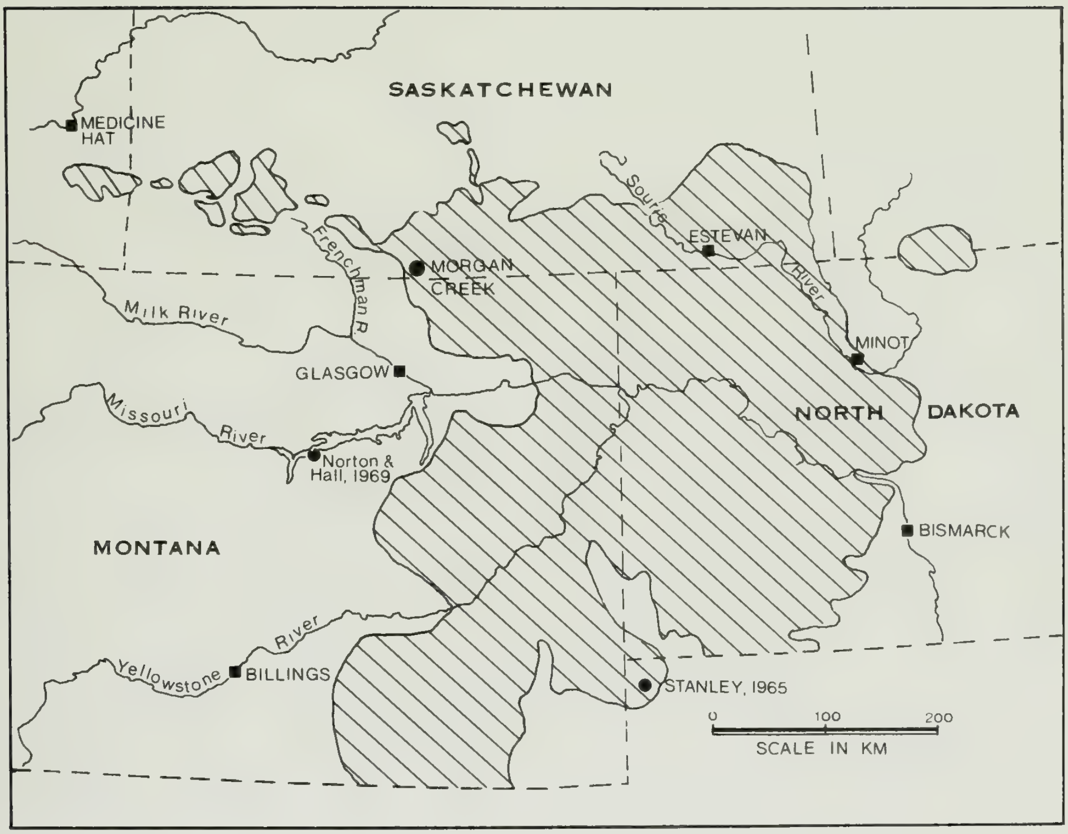

FIGURE 1. *Location of the Morgan Creek locality in southern Saskatchewan, and the location of other contemporaneous Upper Cretaceous sections. Lined area approximates extent of outcrop and subsurface coal deposits marking the Cretaceous-Tertiary transition.*

Roche 1974).

The preliminary results obtained from the examination of the Morgan Creek section, the Ravenscrag Butte section (Saskatchewan, Canada) and the Braggs section (Alabama, U.S.A.) indicate that the flowering plants did not suffer the severe extinctions across the Cretaceous-Tertiary boundary as did several other groups of organisms, notably the dinosaurs.

Some previous pollen studies of Cretaceous-Tertiary age in the Western Interior have suggested that the terrestrial flora can be divided into a lower "typical" Cretaceous flora, a transition flora covering a short stratigraphic interval, and a "typical" Tertiary flora. The Morgan Creek samples and some unpublished work done by R. Tschudy of the U.S.G.S. indicate that the so-called transition flora does not really exist, and in fact much of the "typical" Cretaceous flora extends into and often through the transition flora, and likewise some of the "typical" Tertiary flora extends downward into Cretaceous horizons. Thus the "transition" area is diluted or extended so that the floristic differences between the Cretaceous and Tertiary become less and less.

The foregoing should not suggest that the angiosperms did not suffer extinction or that the Tertiary flora is an extension of the Cretaceous flora, but rather the following three points are concluded: (1) extinctions of the angiosperms at the Cretaceous-Tertiary boundary are observed at the specific and generic level, but they were by no means extensive and drastic, (2) a gradual, and perceptible transition of angiosperm floristic composition takes place as the evolutionary trends, which developed during the early Upper Cretaceous, continue through the latest Cretaceous and into the Tertiary period, (3) although these floristic changes across the Cretaceous-Tertiary boundary do not suggest sharp climatic changes, the possibility of short-term minor climatic fluctuations cannot be ruled out.

This gradual "orderly" change is perhaps reflected in part in an apparent trend from larger, ornamented pollen types typical of animal vector pollination to smaller less ornamented pollen types common to wind pollinated plants. Both animal and wind adapted pollen types are present above and below the Cretaceous-Tertiary boundary, but the relative frequency of these types changes above and below, to suggest a trend towards the perfection of wind pollination during the Tertiary. Conclusive statements as to the significance of this apparent change cannot be made until additional investigations within living ecosystems can be made in order to compare the importance of pollen production, preservation and sedimentation as it is occurring today.

It is, however, known that wind-pollination techniques are an adaptation to seasonality, both in the dry-wet sense and the cool-warm sense. For a discussion of the evolutionary and environmental significance of wind pollination in the angiosperms see Whitehead (1969).

The Morgan Creek flora has also provided considerable information as to the composition and structure of the late Maastrichtian (latest Cretaceous) forests to the extent that a comparable living geographic analogue can be suggested. A land region today which presently supports a vegetational cover taxonomically similar to the Morgan Creek flora is the Southeastern Asian Indomalaysian region. This area today supports a rich and diverse angiosperm flora, of which it has been said that "the Tertiary forests of Malaysia differed very little in their floristic composition from the Rain Forests of today" (In Richards 1966, p. 14). It is here speculated that the terminal Cretaceous flora of southern Saskatchewan differed in perhaps only minor ways from the Tertiary floras of the Indomalaysian regions.

Thus, a study of the present-day floras of the Southeastern Asian and Indomalaysian region would be as close as one could approach the Western Interior Cretaceous floras. Information as to the structure, composition, interrelationships (plant-plant or plant-animal) pollination techniques, nature of seasonality, and competition (again plant-plant or plant-animal) which could be obtained from a study of this selva, seems appropriate to an understanding of Canadian latest Cretaceous environments.

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Awai-Thorne, B.V. 1972. Palynology of the Bearpaw Formation (Campanian) and contiguous upper Cretaceous Strata from the C.P.O.G. Strathmore E.V. Well, southern Alberta, Canada. M.Sc. Thesis, University of Toronto, 126 p.

Sixty-seven taxa of which 16 are stratigraphically significant show a correlation with pollen and spore assemblages from Colorado and to a lesser degree with Montana. The environment of deposition changed from continental or deltaic through marine, and back to deltaic during deposition of the upper Belly River Group, the Bearpaw Formation and lower Horseshoe Canyon Formation.

Axelrod, D.I. and H.P. Bailey. 1969. Paleotemperature analysis of Tertiary floras. Palaeogeog. Palaeoclimatol. Palaeoecol. 6:163-195.

A general trend in lowered annual temperature and increasing ranges of temperatures more marked in interior than in coastal areas can be demonstrated for the Tertiary period through a study of several angiosperm leaf floras.

Barghoorn, E.S. and S.A. Tyler. 1963. Fossil organisms from Precambrian sediments. Ann. N.Y. Acad. Sci. 108(2):451-452.

Filaments ranging in diameter from 0.6μ to 6.0μ indistinguishable from the filaments of extant blue-green algae *(Oscillatoria, Lyngbya et alii)* occur in cherts 1.9 x 10^9 years ago, from the Gunflint Iron Formation, Lake Superior region, Ontario Canada. See also Barghoorn and Tyler. 1965. Science 147(3658):568-577.

Dilcher, D.L. 1973. A paleoclimatic interpretation of the Eocene floras of southeastern North America, p. 39-59. *In* A.K. Graham [ed.] Vegetation and Vegetational History of Northern Latin America. Elsevier Scientific Publ. Co., Amsterdam.

Through a study of foliar physiognomy, wood and pollen of middle Eocene floras of the Mississippi embayment, Dilcher concludes that the climate was one of a seasonally dry to slightly moist moisture regime, and an equable warm temperature to cool-subtropical temperature regime.

Doyle, J.A. 1969. Cretaceous angiosperm pollen of the Atlantic coastal plain and its evolutionary significance. J. Arnold Arbor. Harv. Univ. 50(1):1-35.

A classic study of the sequence of angiosperm evolutionary trends from their earliest appearance in Barremian?-lower Albian? through to the Santonian are clearly monitored. The Cretaceous expansion and diversification of angiosperm pollen are a reflection of their adaptability.

Elsik, W.B. 1968. Palynology of a Paleocene Rockdale lignite Milam county Texas. I. Morphology and Taxonomy. Pollen Spores 10(2):263-314; II. Morphology and Taxonomy (End). Pollen Spores 10(3):599-664.

A descriptive taxonomic study of the pollen and spores from the Wilcox Group of Texas. Certain horizons are characterized by abundant fungal spores. Many extant taxa are recorded and include *Sphagnum, Ephedra, Taxodium, Pinus, Pandanus, Engelhardtia,* *Pterocarya, Carya, Alnus, Quercus(?), Tilia, Nyssa, Typha* and many more.

Erdtman, G. 1943. An introduction to pollen analysis. The Ronald Press Company, New York, 239 p.

The first "handbook" of pollen analysis. The late Prof. Gunner Erdtman's fine contribution (among several others published throughout his long career as a palynologist, ca. 1920-1973) on techniques, chemistry, morphology, dissemination, geographical surveys and other topics relative to the present state (1940's) of knowledge about pollen and spores.

Graham, A. and D.M. Jarzen. 1969. Studies in neotropical paleobotany. I. The Oligocene communities of Puerto Rico. Ann. MO. Bot. Gard. 56:308-357.

Pollen and spore analysis of the San Sebastian Formation indicate that the Oligocene communities of Puerto Rico were not taxonomically much different than they are today. The Puerto Rican study along with studies from Panama, and Veracruz, Mexico, suggest tropical elements in the modern and fossil floras of southeastern North America were introduced along an isthmian-coastal Mexico route during the early Tertiary or subsequently through long-distant dispersal into tropical outliers (southern peninsula Florida).

Jarzen, D.M. 1973. Evolutionary and paleoecological significance of Albian to Campanian angiosperm pollen from the Amoco B-1 Youngstown borehole, southern Alberta. Ph.D. Thesis. The University of Toronto, 291 p.

The first study of the palynoflora from a continuously cored interval spanning approximately 30 million years of Upper Cretaceous time. The development, radiation and diversity of the angiosperms from their first appearance in the Albian through most of the Upper Cretaceous shows a continuous and gradual evolution of pollen types from the small unelaborate and taxonomically undiversified tricolpates and monosulcates to larger elaborately ornamented and diverse pollen types. Botanical considerations demonstrate that for the younger Campanian flora at least, the co-dominant recurring taxa represent tropical and subtropical families of angiosperms.

Leffingwell, H.A. 1971. Palynology of the Lance (late Cretaceous) and Fort Union (Paleocene) Formations of the type Lance area, Wyoming. Geol. Soc. Am. Spec. Pap. 127:1-64.

Two major floral changes across the Maastrichtian-Paleocene interval from several localities in the Rocky Mountain area are considered to be synchronous. The changes are considered as having regional importance and are consistent with foraminiferal and leaf evidence. (Note: in this author's opinion the "sharp" breaks which create the two so-called major floral changes are due to the local extinctions of taxa which elsewhere [e.g. Morgan Creek, Siberia, U.S.S.R., Gulf Coastal, U.S.A.] continue through the Cretaceous-Tertiary boundary. However, the changes as observed by Leffingwell may indeed reflect local or even subregional floristic changes).

Melville, R. 1966. Continental drift, Mesozoic continents and the migrations of the angiosperms. Nature 211:116-120.

A paper, perhaps written slightly ahead of its time, in which the author suggests the existence of a central Pacific continent, Pacifica, present at the close of the Jurassic. The subsequent break-up and drifting of this land mass during the later Mesozoic can help to explain many of the anomalies of angiosperm distributions.

Muller, J. 1970. Palynological evidence on early differentiation of angiosperms. Biol. Rev. 45:417-450.

A major synthesis of much palynological literature in which the sequential evolution of angiosperm taxa are stratigraphically delineated. The stratigraphic ranges of 135 pollen taxa and reference to the publications in which they were first noted are given in tabular form.

Norton, N.J. and J.W. Hall, 1969. Palynology of the Upper Cretaceous and Lower Tertiary in the type locality of the Hell Creek Formation, Montana, U.S.A. Palaeontogr. Abt. B Palaeophytol. 125:1-64.

A descriptive taxonomic study of an abundant and geographically important flora in terms of Western Interior angiosperm successions. The transition flora as proposed by Norton and Hall does not seem as distinct as shown in their stratigraphic chart, to judge from subsequent pollen studies.

Richards, P.W. 1966. The Tropical Rain Forest. The University Press, Cambridge, 450 p.

To date, still the most comprehensive survey of the world's tropical (and some subtropical) Rain Forest communities. An invaluable reference source.

Roche, E. 1974. Paléobotanique, paléoclimatologie et dérive des continents. Sci. Géol., Bull. 27(1-2):9-24, (Strasbourg, Univ. Louis Pasteur).

The hypothesis of continental drift is supported by careful examination of past floristic patterns of distribution and the evolution of climates during geologic history. Plant provinciality which began during the late Cretaceous and basal Tertiary times reaches a maximum during the mid Tertiary.

Snead, R.G. 1969. Microfloral diagnosis of the Cretaceous-Tertiary boundary central Alberta. Res. Counc. Alberta, Bull. 25:1-148.

The Cretaceous-Tertiary boundary is located on the basis of floristic changes and the transitional nature of the flora from the Edmonton Formation (Maastrichtian) through to the overlying Paskapoo Formation (basal Tertiary). Snead suggests that the boundary lies somewhere in the upper coaly interval of the Edmonton Formation, a section of approximately 39.6 meters (130 feet).

Srivastava, S.K. 1970. Pollen biostratigraphy and paleoecology of the Edmonton Formation (Maestrichtian). Alberta, Canada. Palaeogeog. Palaeoclimatol. Palaeoecol. 7(1970):221-276.

Based on nine pollen assemblages (primarily angiosperm) the 256 meters (840 feet) of Upper Cretaceous Edmonton strata are zoned. The assemblages indicate a prevailing subtropical, humid climate which supported a tropical Rain-Forest community during the deposition of the lower Edmonton rocks, while later floras show an increase in the temperate element. According to Srivastava, the flora of the upper most part of the Edmonton Formation at best suggests a warm temperate climate.

Stanley, E.A. 1965. Upper Cretaceous and Paleocene plant microfossils and Paleocene dinoflagellates and hystrichosphaerids from northwestern South Dakota. Bull. Am. Paleontol. 49(222):179-378.

Palynomorphs recovered from four stratigraphic sections are used to zone the Upper Cretaceous and Lower Tertiary strata from Harding County, South Dakota. The botanical affinities suggested for the Paleocene pollen and spores indicate a temperate climate, although at least four genera of tropical to subtropical ferns are present.

Tschudy, R.H. 1971. Palynology of the Cretaceous-Tertiary boundary in the northern Rocky Mountain and Mississippi embayment regions. Geol. Soc. Am. Spec. Pap. 127:65-111.

A comparison of the palynofloras of the Rocky Mountain and Mississippi embayment regions shows a marked difference between the two areas. The western floras are characterized in part by such genera as *Aquilapollenites, Wodehouseia* and *Proteacidites,* while southeastern sediments yield abundant *Rugubivesiculites* and Normapolles pollen types. These differences are perhaps due to the two regions being separated during late Cretaceous time by the wide north-south trending epeiric seaway.

Whitehead, D.R. 1969. Wind pollination in the angiosperms: Evolutionary and environmental considerations. Evolution 23(1):28-35.

Wind pollination in the angiospermae may have paralleled the evolution of the deciduous habit, which it has been suggested evolved as a response to seasonal drought as the angiosperms migrated northward during the early Cretaceous. An examination of present tropical seasonal environments and the fossil record of deciduous and wind-pollinated angiosperms supports the hypothesis that the conditions peripheral to the tropics would favour the evolution of wind pollination.

Willis, J.C. (1897) 1966 (revised by H.K. Airy Shaw). A Dictionary of the Flowering Plants and Ferns. The University Press, Cambridge, 1214 p.

The standard reference source for the spelling, author, distribution, synonomy and species numbers of all known taxa of angiospermae, gymnospermae and pteridophyta *(sensu lato).*

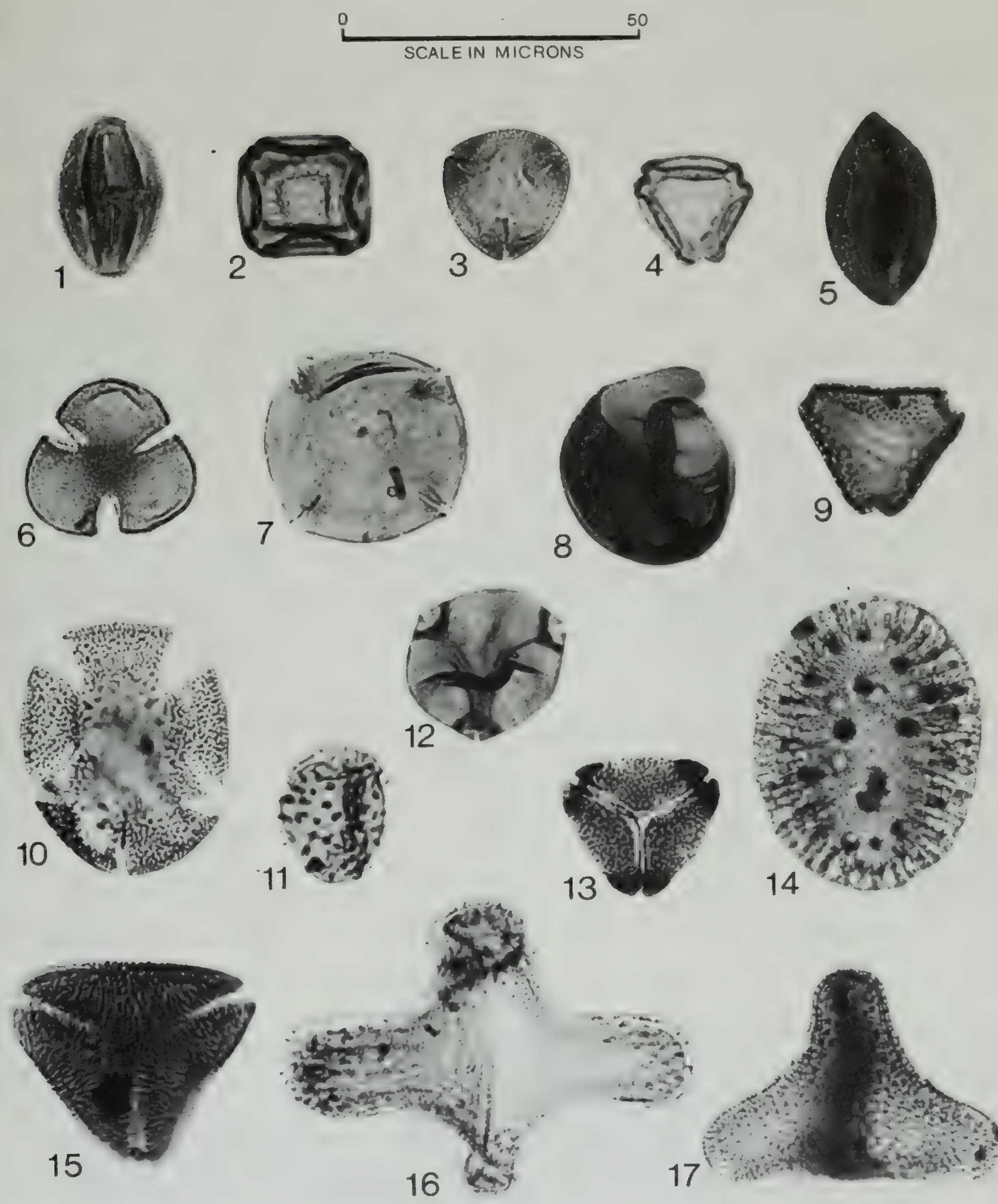
Wodehouse, R.P. 1965. (facsimile of the edition of 1935). Pollen Grains. Hafner Publishing Co., New York, 574 p.

A fine introduction to the science of palynology.

PLATE I. *Selected Maastrichtian and Paleocene palynomorphs from southern Saskatchewan. 1. A tricolporate form comparable to the Anacardiaceae; 2. Four porate form similar to some members of the Ulmaceae; 3. A tridemicolpate type as observed in the Loranthaceae; 4.* Alnus-*type; 5. A monocolpate form of Palmae; 6. The characteristic tricolpate grain of* Gunnera*; 7. An unknown fourcolpate grain; 8. A unique form with a spiral aperture referable to some Berberidaceae; 9. A triporate pollen grain comparable to some members of the Proteaceae; 10. A polycolpate form of unknown affinities. 11. The spinose pollen grain of* Pandanus*; 12. An extinct form referred to as* Kurtzipites*; 13. A syncolporate form; 14. The extinct and characteristic* Wodehouseia *pollen type; 15. A tridemicolpate pollen grain very similar to extant Loranthaceae; 16 and 17. Two forms of the extinct pollen genus* Aquilapollenites.

PLATE I

MAASTRICHTIAN AND PALEOCENE PALYNOMORPHS FROM SOUTHERN SASKATCHEWAN



PHYTOPLANKTON CHANGES NEAR THE CRETACEOUS-TERTIARY BOUNDARY

Geoffrey Norris

Microfloral changes near the Cretaceous-Tertiary boundary are recorded principally by spores and pollen occurring in terrestrial and marine sediments, and by dinoflagellate cysts and calcareous nannoplankton (coccoliths and discoasters) confined to marine strata. Other plant microfossils occur less commonly but include silicoflagellates, diatoms, and various other algal groups of organic, calcareous or siliceous composition.

Evolution, distribution, and changes in abundance and diversity of Phanerozoic phytoplankton have been reviewed by Lipps (1970), Tappan (1971) and Tappan and Loeblich (1971), who have noted a general decrease in diversity of dinoflagellates and calcareous nannoplankton at the Cretaceous-Tertiary boundary and a recovery during the Eocene. Detailed information on dinoflagellate species distribution in the Cretaceous and Tertiary has been presented recently by Harker and Sarjeant (1975). Worsley (1974) underlined the importance of the massive extinction of Cretaceous coccoliths at the end of the Maastrichtian (latest Cretaceous) and the evolution of a new calcareous nannoflora during the succeeding Paleocene (basal Tertiary).

Preliminary unpublished work on dinoflagellates in a relatively complete marine section across the Cretaceous-Tertiary boundary in Alabama has indicated the dominance of chorate cysts (notably *Spiniferites*, *Achomosphaera*, *Areoligera*, and *Cyclonephelium*) in the Upper Maastrichtian Prairie Bluff Chalk. A regressive interval is indicated near the hardground marking the Cretaceous-Tertiary boundary (Worsley 1974) by the influx of abundant terrestrial miospores, tracheids, and cuticle fragments. Dinoflagellate cysts remain relatively common, however, suggesting that fully marine conditions prevailed at this time. Proximate cysts (*Deflandrea*, *Diconodinium*, *Astrocysta*) also become common at this horizon which may be due to a decrease in paleotemperature (Norris and Dörhöfer in press) or to environmental changes attendant on a nearby shoreline (Downie, Hussain and Williams 1971). The latter possibility appears unlikely, however, in view of the continued common presence of proximate cysts in the overlying Paleocene Clayton Formation which appears to have been deposited in an offshore environment.

Phytoplanktonic changes between the Cretaceous and Tertiary have been interpreted in various ways, none of which are entirely satisfactory. Part of the problem concerns the inadequacies inherent in relating fossilized remains to a biotic model. Fossilized microplankton are enormously abundant and very often highly diverse, but the problem of relating these data to past productivity, their trophic level, degree of niche specialization and so on has not been entirely solved. Nevertheless, a rather complete micropaleontological record exists and has allowed a number of interpretations.

Fluctuations of sea level causing transgressions and regressions are frequent in the geologic record and have been invoked to explain massive extinctions. Quaternary eustatic changes of several hundred feet, however, have had little effect on the taxonomic composition of the marine and terrestrial biota. There is little doubt that these fluctuations effect distribution and isolation of populations and thereby may affect evolution by allopatric speciation of certain groups. But this effect would not necessarily have global significance. On the other hand, a marine transgression was initiated about 100 million years ago in many parts of the world and culminated with the widespread flooding of large continental areas in the Upper Cretaceous which in part may be related to rapid late Cretaceous sea floor spreading in the Atlantic (Douglas, Moullade and Nairn 1973). As Tappan (1968) has argued, this major transgression may have been accompanied by nutrient depletion in the oceans which may have led to the demise of major phytoplankton groups forming the base of the food chain. This in turn could have had disastrous effects on dependant animal grazers and carnivore populations. If decimation of phytoplankton did occur at this time, a significantly large decrease in total global photosynthesis would be expected. This would have led to a decrease in atmospheric oxygen and an increase in carbon dioxide. Deleterious effects on animal life on land and in the sea would have followed through oxygen starvation and by carbon dioxide poisoning when the atmospheric level of the latter became greater than a few percent (Tappan and Loeblich 1971). Any changes to atmospheric composition, however, are unlikely to have been long-lasting. Recent calculations (Dimroth and Kimberley 1976) suggest that present atmospheric levels of oxygen could be generated by natural processes within 3 million years and maintained through carbon burial and negative feedback effects of rock weathering and oxidation of volcanic hydrogen gas. Carbon dioxide levels are probably controlled and maintained near current values by the large reservoir of dissolved carbon dioxide in the oceans which represents 98% of total carbon dioxide in the atmosphere and hydrosphere combined. Short term atmospheric carbon dioxide fluctuations would require a few thousand years to attain equilibrium with sea water, depending on the rate of turnover of deeper waters (Tappan and Loeblich 1971).

The effect of a changing carbonate compensation depth (CCD) in the oceans has been discussed recently by Worsley (1974). He has argued that high rates of photosynthetic reduction of carbon dioxide due to the late Cretaceous calcareous nannoplankton bloom eventually led to a climatic deterioration related to changing atmospheric composition. This caused polar cooling of sea water, increased vertical and horizontal stratification of sea water, and thus increasing the solubility of carbon dioxide in high latitudes and deep water. This effect, combined with the depletion of calcium carbonate in the oceans due to evolution of calcareous planktonic organisms during the late Cretaceous caused the rapid migration of the CCD into the photic zone at about the time of the massive nannoplankton extinctions. The sparse nannoflora surviving into the early Tertiary was dominated by taxa tolerant of conditions which are generally adverse to growth of extant oceanic nannoplankton. Worsley cites as evidence for a shallow CCD the widespread development of hardgrounds at the Cretaceous-Tertiary boundary in shallow marine shelf sediments as well as in deep oceanic sequences.

The possibility of drastic changes of the CCD at the Cretaceous-Tertiary boundary is still a moot point, but is a possible example of the particularly severe effect that an environmental change can have on a mature global ecosystem such as the one that undoubtedly existed at the end of the Cretaceous (Tappan 1971). An ecosystem collapse of this type has been related by Tappan to changes to which it cannot readily adapt, such as climatic fluctuations, changing extent of seas, or prominent evolutionary events. The generally impoverished Paleocene biota is believed to represent the effects of a rejuvenated and immature global ecosystem.

Lipps (1971) has placed emphasis on the effects of differing ocean temperatures on planktonic evolution and extinction. According to his hypothesis, warm high latitude seas eliminate both horizontal and vertical habitats and barriers to competition on a world-wide basis, thus causing extinctions. Conversely, cool high-latitude seas create vertically- and horizontally-distributed thermal barriers to competition, thus increasing speciation by horizontal and vertical isolation of populations. Paleo-temperature curves based on oxygen isotope ratios in calcareous organisms indicate an approximate 30 million year cycle (Dorman 1968), average temperatures increasing from minima of approximately 15°C about 100 million years ago and again at 65 million years ago. Each was followed, in about 15 million years by maxima of 20-25°C (Frakes and Kemp 1973; Thompson and Fischer 1975). More detailed work by Douglas and Savin (1974) on Cretaceous oxygen isotope ratios is based on planktonic and benthonic foraminifera and nannoplankton from sites in the central Pacific which lay close to the equator throughout the Cretaceous. Near-surface isotopic temperatures show a thermal maximum close to 30°C between 105-95 million years ago and then a gradual decline to about 18°C at the Cretaceous-Tertiary boundary. Bottom temperatures were consistently cooler, but they found no evidence for a <u>major</u> thermal event at the Cretaceous-Tertiary boundary. Discrepancies between these paleotemperature studies are probably related to different habitats of taxa used in compilations, different latitude positions, and to uncertainties of radiometric ages and their correlation with biostratigraphic stages (Obradovitch and Cobban 1975). There seems little doubt, however, that global temperatures declined in the latest Cretaceous and that a warming trend culminated in the Eocene with the spread of thermophilic taxa polewards.

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Dimroth, E. and M.M. Kimberley. 1976. Precambrian atmospheric oxygen: evidence in the sedimentary distributions of carbon, sulfur, uranium, and iron. Can. J. Earth Sci. 13:1161-1185.

The distribution of certain chemicals in sediments suggests an oxygenated atmosphere in the Precambrian. The effects of organic productivity on atmospheric oxygen pressure are discussed.

Dorman, F.H. 1968. Some Australian oxygen isotope temperatures and a theory for a 30-million year world temperature cycle. J. Geol. 76:297-313.

Paleotemperature fluctuations of 5-10°C occur approximately every 30 million years, with minima occurring in the earliest Cretaceous, the mid-Cretaceous, the latest Cretaceous, the uppermost Eocene and the Quaternary.

Douglas, R.G., M. Moullade and A.E.M. Nairn. 1973. Causes and consequences of drift in the South Atlantic, p. 517-536. *In* D.H. Tarling and S.K. Runcorn [eds.] Implications of continental drift to the earth sciences, vol. 1. Academic Press, New York.

Relates stratigraphy and paleontology to geotectonic evolution. Major transgressions are attributed to rapid sea-floor spreading, culminating in the Turonian, and providing a stimulus for speciation in the late Cretaceous. Major regression occurred in the Maastrichtian when spreading in the South Atlantic had slowed or halted.

Douglas, R.G. and S.M. Savin. 1974. Marine temperatures during the Cretaceous. Geol. Soc. Am., Abstracts with Programs 6(7):714.

Oxygen isotope paleotemperatures derived from microfossils in Pacific deep sea sediments near the equator fluctuated during the Cretaceous, declining to about 18°C at the Cretaceous-Tertiary boundary, but no major thermal event was indicated for this time.

Downie, C., M.A. Hussain and G.L. Williams. 1971. Dinoflagellate cyst and acritarch associations in the Paleogene of southeast England. Geosci. Man 3:29-35.

Lower Tertiary microplankton distributions are related to lithology, and thus to ecology and sedimentary environment.

Frakes, L.A. and E.M. Kemp. 1973. Palaeogene continental positions and evolution of climate, p. 539-558. *In* D.H. Tarling and S.K. Runcorn [eds.] Implications of continental drift to the earth sciences, vol. 1. Academic Press, New York.

Discusses paleobotanical indices of Lower Tertiary climate and relates these to isotopic data, putative continental positions, and oceanic and atmospheric energy transport. Warm Eocene and colder Oligocene climates are indicated, the latter heralding extensive ice accumulation in Antarctica.

Harker, S.D. and W.A.S. Sarjeant. 1975. The stratigraphic distribution of organic walled dinoflagellate cysts in the Cretaceous and Tertiary. Rev. Palaeobot. Palynol. 20:217-235.

A detailed and critical documentation of Cretaceous-Tertiary dinoflagellate species distribution throughout the world.

Lipps, J.H. 1970. Plankton Evolution. Evolution 24:1-22.

Discusses Phanerozoic evolutionary history of plankton, and various hypotheses to explain extinctions and radiations. Sea water temperature fluctuations are concluded to be major factors in controlling speciation and radiation.

Norris, G. and G. Dörhöfer. (in press). Upper Mesozoic dinoflagellate biogeography. Abstr. 2nd N Am. Paleontol. Conv., J. Paleontol.

The nature and extent of Cretaceous dinoflagellate provinces are linked to fluctuations in sea water temperatures.

Obradovich, J.D. and W.A. Cobban. 1975. A time-scale for the Late Cretaceous of the western interior of North America. Geol. Assoc. Can. Spec. Pap. 13:31-54.

The most recent compilation on radiometric ages of bentonites associated with faunal zones, in which the Cretaceous-Tertiary boundary is placed between 64 and 65 million years, and the ages of Upper Cretaceous stage boundaries are determined with an accuracy of less than one million years.

Tappan, H. 1968. Primary production, isotopes, extinctions and the atmosphere. Palaeogeogr. Palaeoclimatol. Palaeoecol. 4:187-210.

Variations in phytoplankton abundances and photosynthesis are linked to putative fluctuations of atmospheric oxygen and thus to selective extinctions of animal taxa at the Cretaceous-Tertiary boundary and other times. Oceanic nutrient depletion due to low continents, equable climates, and less upwelling is favoured as an ultimate control on phytoplankton abundance.

Tappan, H. 1971. Microplankton, ecological succession and evolution. Proc. N Am. Paleontol. Conv., H:1059-1103.

The global ecosystem has shown three major cycles of evolutionary succession, each culminating in a highly structured community which is stable until a marked physical or biological change caused ecosystem collapse. The collapse in the Maastrichtian-Danian was followed by a period of adjustment while marine phytoplankton productivity regained a high level and allowed the terrestrial ecosystem to again diversify.

Tappan, H. and A.R. Loeblich. 1971. Geobiologic implications of fossil phytoplankton evolution and time-space distribution. Geol. Soc. Am. Spec. Pap. 127:247-340.

Discusses in detail the distribution and evolution of important phytoplankton groups since the Precambrian, their interaction with the physical environment, their productivity, and the effects of the latter on sediments and the composition and chemistry of sea water and the atmosphere. Phytoplankton periodicity is concluded to be an evolutionary stimulus to marine and terrestrial faunas on a global scale.

Thompson, I. and A.G. Fischer. 1975. Size and diversity of pelagic organisms undergo cycles. Geol. Soc. Am., Abstracts with Programs 7(7):1298.

The size and diversity of marine planktonic, nektonic, and benthonic faunal groups appear to peak at times of low productivity and high paleotemperature at approximately 32 million year intervals, including peaks in the Upper Cretaceous and the Eocene. Size variation is believed to be an adaptive response to environmental stress.

Worsley, T. 1974. The Cretaceous-Tertiary boundary event in the ocean, p. 94-125. *In* W.W. Hay [ed.] Studies in Paleo-Oceanography. Soc. Econ. Paleontol. Mineral. Spec. Publ. 20:94-125.

An apparently world-wide unconformity occurs at the Cretaceous-Tertiary boundary in both deep-sea and shallow marine shelf carbonate sediments, the hiatus is attributed to a migration of the carbonate compensation depth into the photic zone at the end of the Cretaceous due to oceanic nutrient and carbonate depletion.

MELANINS AS PALAEOBIOLOGICAL AND PALAEOENVIRONMENTAL INDICATORS?

K.A. Pirozynski

Melanins are dark polymeric pigments of widely different chemical composition, and as yet unknown molecular structure. They occur in most groups of living organisms. In the animal kingdom and at least some members of the fungi the melanins are of the indole type, i.e. they are the product of enzymatic oxidation of tyrosine (Ellis and Griffiths 1974). The usual sites of melanin deposition are the external parts of organisms (skin, integument and outer wall of cells), though melanin can occur in the internal organs as well. Being comparatively stable both chemically and physically the melanins have a bearing on the formation of humus in soils, and its preservation in the geological record. Melanized components of fungi in soils, for example, are more resistant to microbial degradation than their unmelanized components (Kuo and Alexander 1967). This resistance, together with the ability to withstand the rigours of fossilization and subsequent laboratory extraction imparted to fungi by the presence of melanin, undoubtedly account for the preponderance of highly melanized propagules in the fossil record.

The role of melanin in the adaptive colouration of insects and lower vertebrates is better understood than its function in screening heat and harmful radiation, or in serving as a barrier to water loss under conditions of osmotic stress. Most fungi that are highly resistant to harsh environments contain melanin. Strongly melanized forms are not only characteristic of tropical deserts exposed to intense UV radiation, but also of polar regions where aridity (through freezing) is the chief life limiting factor. There can be little doubt that melanin functions also as a photoprotector. Melanogenesis in animals is initiated in response to UV radiation. The situation in fungi is less clear. It is known that fungal tyrosinase is produced under conditions which are unfavourable for growth, and that in many fungi survival measures such as conversion from vegetative to sporulating phase or initiation of a resistant (usually strongly melanized) sexual state is triggered by exposure to UV radiation. However there is no unequivocal evidence that melanin synthesis in these fungi is actually induced by irradiation. Indeed, some evidence points to the contrary (Leach 1971). Nevertheless, studies on diverse organisms, including fungi, point to a direct correlation between the degree of melanization of cells and their sensitivity to harmful radiation. For example, melanized spores of certain ascomycetes are more resistant to gamma radiation than spores of fungi without pigments, or of fungi that produce pigments other than melanin. Interestingly, alpine populations of melanized fungi are significantly more resistant than their lowland counterparts (Mirchink et al. 1972). In *Botryodiplodia*, in which some viable spores are not pigmented, the germination of the latter is inhibited by 2400 Å UV after less than one sixtieth of the exposure effective against pigmented spores (Uduebo and Madelin 1974).

The action of melanin appears to be in binding free radical products which, being unstable and chemically active, are harmful to the cell. Such radicals may arise as by-products of metabolic processes within the cell, though the primary agents of their induction are more likely to be UV and ionizing radiation. The pronounced electron accepting capacity of melanin not only facilitates interaction with free radical products, but also allows the polymer to capture electrons from sources outside its own molecule. Melanin, therefore, is sensitive even to low energy photons of light (Lukiewicz 1972). This capacity to deal with harmful products of radiation may have preadapted melanins primarily as radio-protectors rather than osmo-regulators or agents of camouflage colouration. The universality of its presence in the living world makes it an adaptation nearly as old as life itself. It must be added, however, that this protection is not the exclusive domain of the melanins for there are other pigments which perform the same function, but apparently less efficiently, in animals, plants and fungi.

Strong mutagenic agents, such as UV and gamma radiation or nitrous acid, that inactivate DNA or cause mitotic gene conversion and crossing over (as shown in studies on diploid yeasts [Davies et al. 1975]), are the products of cosmic phenomena or their interaction with the stratosphere. The record of such physical phenomena may be preserved in the occurrence and distribution of melanins. This relationship was expressed by Blinov (1973), who remarked "... that melaninogenesis depends on meteorological factors", and added: "The high electron acceptor capacity of melanins, the presence of free radicals in them, and their semi-conductor properties may be related to the mechanisms of migration of energy in biological systems". Could these properties be also related to energy migration outside of our biosphere, and — if the melanins stamped the register of geologic time — to its migration in the past?

It has been suggested that mutagenic and lethal waves of far UV may have triggered biotic change and diversity in pre-Silurian times. I cannot answer the question of what role melanins played in the proliferation of life approximately 500 million years ago. Nor am I in a position to offer answers to questions pertaining to melanins in context of the central theme of our discussions. However, it may not be merely a matter of coincidence that the terminal Cretaceous events are followed by significant proliferation and morphological diversification of highly melanized spores of ascomycetes, or that today brain melanins occur in mammalian carnivores and primates but not in monotremes, marsupials or insectivores. Mammalian neuromelanin may then be a post-Cretaceous phylogenetic development even if its deposition is limited to more ancient parts of the brain.

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Blinov, N.O. 1973. Review of S.P. Lyakh and E.L. Ruban's Microbial Melanins (Publ. Nauka, Moscow 1972, 185 p.). Mikrobiologiya 42(4):752-754.

The genetics of melanin producers, the control of, and the environmental influences on melanogenesis are analyzed. Great attention is paid to the utility of melanins for their producers and their role in global biotic cycles. Finally, the dependence of melanogenesis on meteorological factors is stressed.

Davies, P.J., W.E. Evans and J.M. Parry. 1975. Mitotic recombination induced by chemical and physical agents in the yeast *Saccharomyces cerevisiae* Mutat. Res. 29(3):301-313.

The treatment of diploid cultures of yeast with UV, gamma rays and nitrous acid and other agents increases cell death, mitotic gene conversion and crossing-over. These agents were effective in the order UV > nitrous acid > gamma rays.

Ellis, D.H. and D.A. Griffiths. 1974. The location and analysis of melanins in the cell walls of some soil fungi. Can. J. Microbiol. 20:1379-1386.

Melanins extracted from the fungi are of indolic nature, belonging to the same class of pigments described previously from plant and animal material.

Kuo, M.J. and M. Alexander. 1967. Inhibition of lysis of fungi by melanins. J. Bacteriol. 94(3):624-629.

The resistance of *Aspergillus nidulans* hyphae to lysis by an enzymatic mixture results from the presence of melanin in the fungal wall. Melanin also appears to combine with and protect certain sustrates from decomposition. Melanin is found to be highly resistant to microbial degradation.

Leach, C.M. 1971. A practical guide to the effects of visible and ultraviolet light on fungi, p. 609-664. *In* C. Booth [ed.] Methods in Microbiology, vol. 4, Academic Press, New York.

The direct and indirect effects of light (of all wavelengths) on fungi are discussed in a context of practical considerations for microbiologists. The mutagenic and lethal effects of UV have long been known, but little is known of the role of pigments in fungi. They are thought to act as photoreceptors for various photobiological phenomena and/or as protectors against UV. Wavelengths of radiation in the near UV and blue regions of the spectrum are effective in inducing pigment formation in some fungi.

Lukiewicz, S. 1972. The biological role of melanin. I. New concepts and methodological approaches. Folia Histochem. Cytochem. 10:93-108.

The roles of natural photoprotectors, endogenous rH regulators, cellular radioprotectors, and of a "hormone" involved in homeostatic reactions, are ascribed to melanins and melanoproteins on the grounds of recent investigations. These assumptions are shown to be qualitatively consistent with the observed facts. It is emphasized, however, that a rigorous verification of the new concepts would require more exact, quantitative, methodical approaches, including work on living objects. This paper initiates a series of such experimental studies.

Mirchink, T.G., G.B. Kashkina and Yu. D. Abaturov. 1972. The resistance of fungi with various pigments to γ radiation. Mikrobiologiya 41(1):83-86.

Non pigmented and yellow pigmented fungi are least resistant, while species with melanin show greatest resistance to gamma radiation. In the latter group, alpine strains are more resistant than plain strains from the same species.

Uduebo, A.E. and M.F. Madelin. 1974. Germination of conidia of *Botryodiplodia theobromae* in relation to age and environment. Trans. Br. Mycol. Soc. 63(1):33-44.

The characteristics of hyaline nonseptate (initial stage) and pigmented septate (more mature stage) conidia are compared. The first type normally germinates faster but is more vulnerable to supraoptimal temperatures and succombs to UV (2400 Å) much faster than the second type.

THE GEOMAGNETIC FIELD AND THE CRETACEOUS-TERTIARY EXTINCTIONS

John H. Foster

The discovery that the Earth's magnetic field has undergone reversals of polarity was made nearly 70 years ago. Sequences of these reversal events were documented in oceanic sediment cores during the 1960's, providing data leading to the establishment of the sea floor spreading hypothesis and the new global tectonics. This has been summarized in a very readable manner by Horsfield and Stone (1972).

In the past 10 years, paleomagnetism has developed from a small and obscure topic to an essential discipline in geoscience. An outstanding example of its utility has been documented by Ryan et al. (1974).

Remanent magnetism in sedimentary rocks

The most recent work pertinent to the Cretaceous-Tertiary problem is a paleomagnetic study of the Upper Cretaceous part of the Scaglia Rossa pelagic limestone in the section at Gubbio, Italy. This is reported by Lowrie and Alvarez (in press) as a sequence of magnetic polarity zones that correspond with the polarity sequence inferred from marine magnetic anomaly profiles. The Cretaceous-Tertiary boundary is found near the top of the reversed polarity interval immediately preceeding anomaly 29.

In a companion paper (Alvarez et al. in press) correlations are presented between magnetic polarity and foraminiferal zones, and their assumption that these are probably accurate to the nearest metre. Part of this uncertainty comes from the remanent magnetization being postdepositional in nature, and the remainder from upward mixing of the fossils after deposition. A very careful consideration of these uncertainties is needed in any detailed study such as the relation of the geomagnetic field to the Cretaceous-Tertiary extinctions.

The arguments in favour of the remanent magnetization of sediments being postdepositional can be quite firmly established. Work by Larson et al. (1969) documented a close relationship between the stability of magnetization of an igneous rock and the effective grain size of the magnetic minerals in the rock. The observed size distribution, for stable rocks, peaked at 1.0μ. Less stable rocks had larger magnetic mineral grains than the more stable rocks. From the work of Strangway et al. (1968) the amount of magnetic material needed to explain the observed magnetization of sediments would be on the order of magnitude of 0.0005 parts per million. The size range and abundance of magnetic minerals in deep-sea sediments is consistent with these estimates. The experimental work of Khramov (1968) showed that the magnetization of sediments was locked in when the water content of the sediment decreased from the order of 70% to the order of 30%. More recent work on this problem has been reported by Løvlie et al. (1971), Kent (1973) and Løvlie (1974).

Origin of the sedimentary record

From the empirical evidence of the recovery of magnetic stratigraphy from deep-sea sediment cores taken in areas of intensive burrowing activity, we know that postdepositional remanent magnetization must be acquired below the burrowing zone, at some depth determined by sediment density, particle size and particle angularity. In the correlation of a layer of microtektites with the Brunhes-Matuyama boundary, Glass and Heezen (1967) found them dispersed through a layer 30 to 60 cm thick. The origin of these microtektites, if indeed it was from the collision of a comet with the Earth, can be thought of as geologically instantaneous. Yet these particles, with a mean size of 200μ and a range of 10 to 1000μ, were found mixed upwards into sediments deposited during the 40,000 to 100,000 years following this microtektite shower.

In a study of sediment mixing across what was then thought to be the Pliocene-Pleistocene boundary, McIntyre et al. (1967) studied the abundance of some nannofossils (discoasters) of a mean diameter on the order of 5μ. They concluded that the observed distribution of the discoasters resulted from their vertical mixing. Discoasters above the boundary were generally corroded, fragmented and often found in clumps with adhering sediment, indicating reworking. Below the boundary the majority were intact and relatively unworn. The discoasters showed an exponential decrease in abundance above the boundary. A concentration of e^{-1}, or 0.37 times maximum concentration was reached in 50 cm or less. The tail of the exponential curve went as far as 5 m above this point. On the basis of other nannofossils (coccoliths), of a size range of 2 to 10μ, they found the boundary to be a mixed zone 30 to 40 cm in width.

In a detailed study of the correlation between the extinction of a radiolarian species, and a magnetic reversal, Hays (1970) also found similar exponential decreases in abundance and a mixing layer of 20 to 30 cm. So little is known about bottom water winnowing and the activities of organisms inhabiting the water-sediment interface that we have no details of how pelagic sediments are in fact mixed, or how mixing processes might differ from place to place. Winnowing without burrowing provides laminated sediments. Winnowing with burrowing results in mottled sediments.

A model for the mixing of pelagic sediments, proposed by Berger and Heath (1968), consisted of a mixed layer with a gradually upward moving historical layer below it. This model predicts an exponential increase at first appearance, and an exponential decrease at extinction of microfossil indicators. They drew a careful distinction between the level of first occurrence of a species, as recorded by a stratigrapher, and the level of the sediment-water interface when that species was first deposited. This latter level, which they call the level of first appearance, is a time stratigraphic boundary. It is separated from the level of first occurrence, a rock stratigraphic boundary, by a distance corresponding to the thickness of the mixed layer. The time stratigraphic and rock stratigraphic boundaries must not be confused in this problem.

The postdepositional remanent magnetization of sediments is an observed, rock stratigraphic boundary. The time stratigraphic boundary can only be calculated, not actually observed. Mixing need not result only from burrowing benthonic organisms. Laminated sediments, such as varved clays, have a mixed layer thickness equal to the distance from the sediment water interface to the depth at which the water content, grain size and grain angularity combine to lock in the remanent magnetization. There is very little empirical evidence available about this thickness. One may quote the results of laboratory redeposition experiments with caution, for the organic slimes present in the real sedimentary environments cannot be duplicated. These slimes could well promote, or inhibit, the rotation of the small magnetic minerals at depths quite different than the depths predicted from laboratory work. When the fluctuations in the activity of burrowing organisms and changes in the rate of winnowing by bottom currents with climate, are added to the case of the simply laminated sediments, the computation of the thickness of the mixing layer becomes increasingly approximate.

An approximation to the thickness of the mixing layer can be made from other correlative data. However, assumptions of synchroneity of the parameter being correlated may not be correct. A fall of microtektites, a layer of volcanic ash, a climatic change, or a faunal change recorded in the sediments could lead or lag some change in the postdepositional remanent magnetization in quite different ways in different sedimentary regimes. From the small amount of available physical evidence, the thickness of the mixed layer, that is, the physical separation of the observed rock stratigraphic boundary from the inferred time stratigraphic boundary at some computed distance above it in the section, is on the order of a few 10's of cm. Stratigraphy would be a much simpler discipline if this difference could be ignored.

Gaps in the sedimentary record

Unfortunately, all of the carefully reasoned estimates of the location of a time horizon in sections, such as the Cretaceous-Tertiary boundary, can be in serious error because of a hiatus caused by nondeposition, scour, or solution. Hiatuses are much more common in sediments than was once believed. For example, the Blake Event, a short reversed polarity event in the Brunhes normal polarity epoch, is well documented by Smith and Foster (1969), although Opdyke (1972) noted that the event is found in only about 10% of the cores which ought to show it.

Worse yet, the Cretaceous-Tertiary boundary is marked by one of the more pronounced hiatuses of the Phanerozoic. Worsley (1971) noted that the unconformity across the Cretaceous-Tertiary boundary in deep sea carbonate sediments is much greater in the ocean basins than on the continents and that a transitional sequence will probably never be found. How the Gubbio section, with an apparent continuous sequence of pelagic calcareous fossils, escaped this world-wide hiatus is somewhat puzzling. We have no real assurance that it did escape.

Worsley (1974) later estimated, from inferred sedimentation rates, that the hiatus seems to be on the order of 100,000 to one million years for continental shelf sections, and more for deeper water, pelagic sections. This seems to have been caused by a large upward movement of the carbonate compensation depth, rather than a sedimentary bypassing or erosional unconformity (see Norris paper). If one thinks of pelagic sediments as being a small fraction of clay-sized mineral particles and a much larger fraction of biogenic material diluting this clay fraction by 10 or 100 to one, the Cretaceous-Tertiary boundary may well have been recorded by postdepositional remanent magnetization without the correlative microfossil indicators.

There is, however, little hope of recovering this magnetization. For some reason, the magnetization seems to survive only when the clay is adequately buffered by biogenic debris. Opdyke and Foster (1970) found that only rarely do clay sediments of the deep ocean basins provide more than a million years of record before the postdepositional remanent magnetization is overwhelmed by an overprint of chemical remanent magnetization. From all of this, one can see that a study of many sections (particularly of carbonate rocks) spanning the Cretaceous-Tertiary boundary will be frustrated by Catch-22: the boundary cannot be studied because it isn't there.

<u>Reversals as a means of establishing synchroneity</u>

As well as the Gubbio section, there are other sections throughout the world which are said to contain a "complete" record of the Cretaceous-Tertiary boundary. The word "complete" can be quite misleading. For some fossil indicators, "complete" implies no gaps of perhaps greater than 10 million years. Others imply no gaps greater than one million years. The duration of such time gaps is subject to much dispute since there are few suitably precise controls on the absolute ages of horizons near the Cretaceous-Tertiary boundary, and many of the sub-divisions of the late Cretaceous and early Tertiary are assigned ages on little more than interpolative guesswork. Even if the Gubbio section were of monotonous lithology with an ideally constant sedimentation rate, it would be difficult, if not impossible, to calculate the location of the time stratigraphic Cretaceous-Tertiary boundary in terms of either the magnetic or microfossil record. Only the rock stratigraphic boundary can be directly observed. Since the Gubbio section is neither monotonous nor likely to be of a constant sedimentation rate, the chances of a precise estimation of the size of the hiatus, if any, at the boundary, are poor indeed.

In spite of all of the uncertainties, there is much to be gained from a detailed study of the fluctuations of the postdepositional remanent magnetism and the sedimentary material for several metres on each side of the alleged boundary at each of the locations in the world where the section has been claimed, by various authors, to be complete. If, for example, the boundary is clearly diachronous beyond the uncertainties of the methods of study, then any catastrophysical model proposed as an explanation of the Cretaceous-Tertiary boundary is discredited. On the other hand, if the boundary is found to be synchronous within the uncertainties of the method, then this may be cited as evidence in agreement with a catastrophic explanation. Such detailed studies, though perhaps difficult, are an important first test of any catastrophysical model.

Reversals correlative with extinctions

As if the difficulties in using the geomagnetic field for correlative evidence in the explanation of massive extinctions at the Cretaceous-Tertiary boundary were not sufficient, the fluctuations of the geomagnetic field may be part of the reason for the extinctions. Uffen (1963) argued that since the Earth's dipole magnetic field goes through zero at the time of a magnetic reversal, its shielding effect would be largely removed. This would expose the Earth to a higher incidence of cosmic radiation than when the field was at full strength. Simpson (1966) attempted to correlate intervals with a high frequency of reversals to periods of accelerated evolution. Others (Waddington 1967, Black 1967 and Harrison 1968) argued that the increase in radiation on the surface of the Earth would be neglible. Alternatively, Harrison (1968) suggested that reversals would be accompanied by climatic changes.

A fascinating link between reversals and extinctions was proposed by Crain (1971). This was a simple and direct mechanism not requiring the intermediate mechanism of cosmic radiation or climatic change. Crain proposed that extinctions are caused directly by the harmful effects on the organism of a reduced magnetic field during a reversal. The effects of low levels of the geomagnetic field in the past on organisms could have been quite significant.* Infertility, changes in locomotion and enzyme alterations could have had a lethal effect on many species. This mechanism would be equally effective on marine and terrestrial organisms since sea water would not shield the former from the effects of changes in the intensity of the geomagnetic field. If stresses from a low field were augmented by an increased cosmic ray flux, ultraviolet radiation and climatic change as well, the effects could well explain the catastrophy shown in the biotic record. The most recent proposed connection between reversals and extinctions is through ultraviolet light irradiation (see Reid paper).

Thus the link between geomagnetic reversals and extinctions may be climate, radiation damage, ultraviolet damage or direct biomagnetic effect. On the other hand, reversals may simply be correlated with the extinctions and

*The Soviet literature on this topic is massive, the Western literature, by contrast, is quite sparse.

some cause unrelated to the reversals. Residents of the Earth may soon have part of the answer to the problem of extinctions should they in fact be related to reversals of the geomagnetic field. Harwood and Malin (1976) have computed that, at the present rate of decay, the dipole field of the Earth will reverse in 2230 AD. Should the low intensity effect be significant it may well be noticeable in our lifetime. Man, the tool bearing hominid, has survived the last dozen or so reversals. We have little choice but to cheerfully assume he will survive this next one.

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Alvarez, W., M.A. Arthur, A.G. Fischer, W. Lowrie, G. Napoleone, I. Premoli Silva and W.M. Roggenthen. (in press). Type section of late Cretaceous-Paleocene geomagnetic reversal time scale. Bull. Geol. Soc. Am.

In this paper the results of four companion papers on the lithostratigraphic, paleontological, and paleomagnetic studies of the Gubbio section are synthesized. The authors propose Gubbio as the magnetostratigraphic type section for the Upper Cretaceous and Paleocene.

Berger, W.H. and G.R. Heath. 1968. Vertical mixing in pelagic sediments. J. Mar. Res. 26:134-143.

The authors' discussion of the assumptions in their mixing model, and the possible consequences of real conditions not following their assumptions, constitute a most important contribution to the understanding of the relationships of magnetic and faunal stratigraphy observed in sediments to what actually happened.

Black, D.I. 1967. Cosmic ray effects and faunal extinctions at geomagnetic field reversals. Earth Planet. Sci. Lett. 3:225-236.

Radiation increase during a reversal would be negligible.

Brunhes, B. and P. David. 1901. Sur la direction d'aimantation dans des couches d'argile transformée en brique par des coulées de lave. C.R. Hebd. Séan. Acad. Sci. 133:155-157.

This was the first of a series of four papers published between 1901 and 1906. The authors solved a number of geological problems with remanent magnetism, for example, the magnetic anomalies of the Puy de Dôme.

Cox, A., R.R. Doell and G.B. Dalrymple. 1964. Reversals of the earth's magnetic field. Science 144:1537-1543.

This was one of a lengthy series of research results by various combinations of these three authors. Their treatment of the problem was incredibly thorough.

Crain, I.K. 1971. Possible direct causal relation between geomagnetic reversals and biological extinctions. Bull. Geol. Soc. Am. 82:2603-2606.

The low magnetic field itself rather than cosmic radiation caused mass extinctions.

Folgheraiter, G. 1896. Variazione secolare dell'inclinazione magnetica. Rend. Att. Real. Accad. Lincei, Cl. Sci. Fis. Matem. Nat. 5:66-74.

Folgheraiter oriented pottery to an original vertical through the study of the drip marks of the glazing. From this orientation, and the measurement of the direction of the remanent magnetization of the pots, he found the magnetic inclination at the time of firing. This was one of a series of papers in Italian. A Rosetta stone to this work is found in his 1899 paper, which was published in French, in a journal edited by none other than B. Brunhes.

Foster, J.H. 1966. A paleomagnetic spinner magnetometer using a fluxgate gradiometer. Earth Planet. Sci. Lett. 1:463-466.

This was an easily duplicated instrument suitable for measuring mechanically and magnetically weak sediments in a somewhat hostile magnetic environment. Within a year, half a dozen copies were in use from Hawaii to Florida in various paleomagnetic laboratories. Within five years, a commercially improved version was in use in over fifty laboratories around the world. Before 1966, the construction of a paleomagnetic laboratory involved one or more man-years of an instrument oriented physicist, or an electrical engineer.

Foster, J.H. 1970. Paleomagnetic stratigraphy of deep-sea sediments. Ph.D. Thesis, Columbia University, New York. 90 p.

This was a summary of published papers authored and coauthored by Foster in the period 1966 through 1969. The data from the equipment built in 1966 produced many more papers by various other combinations of authors such as Burkle, Dickson, Ericson, Glass, Hays, Heezen, Kent, Lowrie, Løvlie, Ninkovich, Opdyke, Saito, Smith, Ryan, Wensink and Wollin.

Glass, B. and B.C. Heezen. 1967. Tektites and geomagnetic reversals. Sci. Am. 217(1):33-38.

Were comets and midwives at the birth of man?

Harrison, C.G.A. 1968. Evolutionary processes and reversals of the earth's magnetic field. Nature 217:46-47.

The effect of direct radiation might not be as great as the effect of climatic change associated with a geomagnetic reversal.

Harrison, C.G.A. and B.M. Funnell. 1964. Relationship of paleomagnetic reversals and micropaleontology in two late Cenozoic cores from the Pacific Ocean. Nature 204:566.

The authors' observations were not consistent with the hypothesis that the Earth's field had reversed every million years unless extremely slow deposition was assumed for the lower portion of the cores. Their data was correct, but the model to which they were trying to make a correlation was incomplete in that it only showed the longer magnetic epochs, and not the shorter events within the second epoch back from the present.

Harwood, J.M. and S.R.C. Malin. 1976. Present trends of the earth's magnetic field. Nature 259:469-471.

The dipole should soon reverse if the present trend continues.

Hays, J.D. 1970. The stratigraphy and evolutionary trends of radiolaria in North Pacific deep sea sediments. Geol. Soc. Mem. 126:185-218.

An extraordinarily thorough documentation of the correlation between a geomagnetic reversal and a radiolarian extinction.

Horsfield, B. and P.B. Stone. 1972. The great ocean business. Hodder and Stoughton, London. 360 p.

This popular account provides a very good insight into the people and events of the first five years of this revolution in geology. Very readable. Probably the best treatment available to date.

Kent, D.V. 1973. Post-depositional remanent magnetization in deep-sea sediment. Nature 246:32-34.

Preliminary laboratory investigations showed that only a small decrease in water content is necessary to lock a postdepositional remanent magnetization into the sediment.

Khramov, A.N. 1968. Orientational magnetization of finely dispersed sediments. [Transl. from Russian] p. 115-119. UDC 550.382.3

A laboratory study of the conditions at the sediment-water interface where an equilibrium exists between the orienting influence of the geomagnetic field and the disorienting influence of Brownian movement.

Larson, E., M. Ozima, M. Ozima, T. Nagata and D. Strangway. 1969. Stability of remanent magnetization of igneous rocks. Geophys. J. Roy. Astr. Soc. 17:263-292.

A relation was found between the distribution of grain size and the spectrum of magnetic hardness for prepared samples and natural rocks.

Linkova, T.I. 1966. Some results of paleomagnetic study of Arctic Ocean floor sediments. [Transl. from Russian] p. 1-4. Def. Res. Bd Can. T-463.

I will never understand why this work was not followed up. Linkova knew the technique could be used to delineate the paleogeomagnetic field and as a means of correlation for oceanic sediments.

Lowrie, W. and W. Alvarez. (in press). Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy. Bull. Geol. Soc. Am.

A first class, state of the art paper on the subject. The preprint was generously provided by Walter Alvarez.

Løvlie, R. 1974. Post-depositional remanent magnetization in a re-deposited deep sea sediment. Earth Planet. Sci. Lett. 21:315-320.

Another lab demonstration of postdepositional remanent magnetization.

Løvlie, R., W. Lowrie and M. Jacobs. 1971. Magnetic properties and mineralogy of four deep-sea cores. Earth Planet. Sci. Lett. 15: 157-168.

Magnetization is postdepositional, or depositional rather than chemical.

McIntyre, A., A.W.H. Be and R. Prekstas. 1967. Coccoliths and the Pliocene-Pleistocene boundary, p. 3-25. *In* M. Sears [ed.] The Quaternary history of the ocean basins. Pergamon Press, New York.

The mixing of discoasters and coccoliths should approximate the mixing of magnetite particles in the size range important for postdepositional remanent magnetization.

Opdyke, N.D. 1972. Paleomagnetism of deep-sea cores. Rev. Geophys. Space Phys. 10(1):213-249.

This is a review to cover the principal developments that occurred in the six years between 1965 and 1971 in the paleomagnetic study of marine sediments.

Opdyke, N.D. and J.H. Foster. 1970. Paleomagnetism of cores from the North Pacific. Geol. Soc. Am. Mem. 126:83-119.

Results of several years work are summarized here.

Ryan, W.B.F., M.B. Cita, M. Dreyfus Rawson, L.H. Burckle and T. Saito. 1974. A paleomagnetic assignment of neogene stage boundaries and the development of isochronous datum planes between the Mediterranean, the Pacific and Indian oceans in order to investigate the response of the world ocean to the Mediterranean "salinity crisis". Riv. Ital. Paleontol. 80:631-688.

This is an unprecedented dating of geological boundaries from the present back to the Oligocene-Miocene boundary at 24 million years ago. It is a magnificent example of the benefits of a multi-disciplinary approach to a difficult problem.

Simpson, J.F. 1966. Evolutionary pulsations and geomagnetic polarity. Bull. Geol. Soc. Am. 77:197-204.

This was an attempt to substantiate Uffen's 1963 hypothesis on the effect of evolutionary rate changes resulting from changes in the ionizing radiation environment resulting from geomagnetic polarity reversals.

Smith, J.D. and J.H. Foster. 1969. Geomagnetic reversal in the Brunhes normal polarity epoch. Science 163:565-567.

The Blake Event has been replicated often enough that there is no doubt of its existence, although the frequent absence of this event in long Brunhes epoch cores did create considerable doubts for quite some time.

Strangway, W.E., E.E. Larson and M. Goldstein. 1968. A possible cause of high magnetic stability in volcanic rocks. J. Geophys. Res. 73:3787-3795.

This was an explanation of why larger opaque grains, from a few microns to 1 mm across, behave as much smaller single domain grains. Of interest to us was their estimate of the volume of a typical sample that needs to be in a single domain form for the observed magnetization. The smallest traces of wind blown dust, contaminating an apparently pure, nonmagnetic sediment, is sufficient to explain the observed remanent magnetization. Neither considered by Strangway, nor explained in the text, is the problem of getting such fine grained material to the bottom of the ocean in a short enough time to keep it as fresh as it is observed to be. The answer is, they take the express elevator to the bottom in the form of fecal pellets (you see, these whales graze on plankton, and.....)!

Uffen, R.J. 1963. Influence of the earth's core on the origin and the evolution of life. Nature 198:143-144.

This put into print a number of the speculations paleomagnetists had been muttering about for many years. Uffen presented an expanded version of this at the International Geological Congress in New Delhi, 1964.

Waddington, C.J. 1967. Paleomagnetic field reversals and cosmic radiation. Science 158:913-915.

The radiation increase during a reversal is concluded to be negligible.

Worsley, T.R. 1971. Terminal Cretaceous events. Nature 230:318-320.

Worsley, T. 1974. The Cretaceous-Tertiary boundary event in the ocean. Soc. Econ. Paleontol. Mineral., Spec. Publ. 20:94-125.

See Russell and Norris papers.

STRATOSPHERIC AERONOMY AND THE CRETACEOUS-TERTIARY EXTINCTIONS

George C. Reid

Uffen (1963) proposed that living organisms might be particularly vulnerable to polarity reversals of the Earth's magnetic field. The causes of polarity reversals are not well understood, but they are known from the paleomagnetic record to have taken place with an approximate frequency of once every few hundred thousand years, or several thousand times since the first appearance of fossilized life forms at the beginning of the Cambrian. Uffen pointed out that during a polarity reversal the Earth's magnetic field is very greatly weakened, and may even disappear entirely, exposing the Earth to an enhanced flux of cosmic rays and possibly leading to increased mutation rates or radiation-induced deaths among living species.

The chief difficulty with Uffen's hypothesis, as was quickly pointed out by several investigators, is that there are really two shields against the direct effects of cosmic radiation — the geomagnetic field and the atmosphere. Even in the absence of the magnetic field, the atmospheric shield would remain intact, and cosmic-ray fluxes at the surface of the Earth would not rise by more than a few percent, certainly not enough to explain widespread faunal extinctions.

Curiously enough, no sooner had Uffen's suggestion been discarded than evidence began to accumulate for a correlation between certain faunal extinctions and geomagnetic polarity reversals that was highly significant statistically. The outstanding example is the work of Hays (1971) on radiolarian extinctions revealed in deep-sea cores, which seemed to show beyond reasonable doubt that polarity reversals were periods of strong environmental stress, at least for these simple planktonic organisms.

The reasons for this effect were widely debated, but no satisfactory conclusions were reached. Among the possibilities discussed were climatic changes associated with polarity reversals and direct magnetic effects on the growth of simple organisms. These only beg the question to a large extent, however, since there was no obvious mechanism for connecting the geomagnetic field with climate, nor was there any convincing biological evidence for magnetic effects on organisms.

Recently, Crutzen et al. (1975) pointed out that solar-proton events associated with major solar flares generate large quantities of nitric oxide (NO) in the stratosphere at high magnetic latitudes, and that this must result in substantial depletions of stratospheric ozone through the catalytic reactions

$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO_2 + O \rightarrow NO + O_2 \ ;$$

(the full chemical reaction scheme is much more complicated than this, but the above reactions form the basis for the ozone depletion mechanism). Since the lifetime of NO in the stratosphere is of the order of years, it is distributed globally by winds and diffusion processes, and the effect on ozone is global in extent. The magnitude of the NO enhancement is illustrated in Fig. 1, which shows the calculated amounts of NO produced by three major solar-proton events, those of November 1960, September 1966, and August 1972. Also shown for comparison are an estimate of the steady-state distribution of odd-nitrogen compounds (NO_x) produced by oxidation of nitrous oxide (N_2O) generated at the surface of the Earth, chiefly by the action of denitrifying bacteria in the soil, and estimates of the amount of NO produced in a year by the ionizing action of galactic cosmic rays, during sunspot minimum (GCR_{min}) and sunspot maximum (GCR_{max}). A major uncertainty in the calculation is the extent to which the free nitrogen atoms formed during the ionization process are in the ground (^4S) or excited (^2D or ^2P) states. Excited N atoms react much more rapidly with oxygen to form NO than ground-state atoms, especially at the low temperatures of the upper stratosphere and mesosphere, and the difference is illustrated by the two curves for each event, corresponding to the extreme assumptions that all N atoms are ground-state ($P_N = 1$) or all are excited ($P_N = 0$).

Obviously, major solar-proton events are important contributors to the

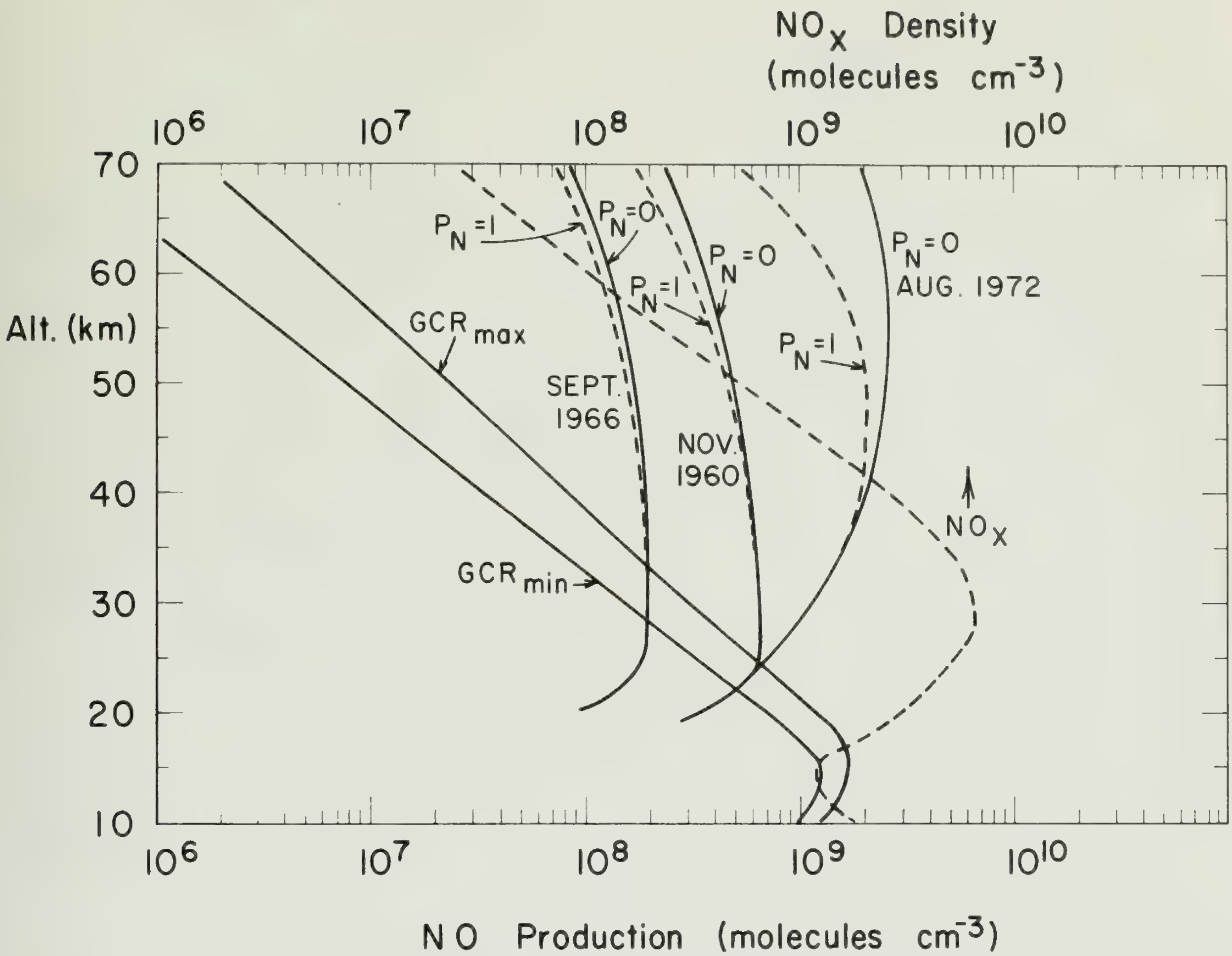

FIGURE 1. *Amount of NO produced in the stratosphere by major solar-proton events and by other natural sources (after Crutzen et al. 1975).*

odd-nitrogen budget of the stratosphere, especially at high magnetic latitudes where the solar protons create NO directly. It should be mentioned in passing that the particle fluxes during these events contain alpha-particles, heavier nuclei, and relativistic electrons, in addition to protons, and these will also produce NO. In the vast majority of events, however, their contribution is much smaller than that of the protons.

The protons themselves usually have steep energy spectra, with fluxes at the lower energies that are much more intense than those at higher energies. In order to reach the top of the stratosphere, a proton requires an energy of about 30 Mev, while the minimum energy needed to reach the troposphere is about 1 Gev (tropospheric NO will be rapidly removed by formation of such soluble compounds as HNO_3 and subsequent washout by rainfall and snowfall). Observation and theory both place the present geomagnetic cutoff latitude (i.e. the minimum geomagnetic latitude attainable) for 30 Mev protons at about 60° (e.g. Reid and Sauer 1967), so that the full stratospheric effects will be felt only at magnetic latitudes higher than this. There will be a range of a few degrees in latitude below 60° (say down to about 55°) within which the cutoff increases to 1 Gev, and partial stratospheric effects occur, but below this latitude there will be little direct effect. As mentioned above, however, transport processes within the stratosphere will carry the NO generated at the higher latitudes to all points within a matter of months. It is also worth pointing out that because of the displacement of the geomagnetic pole with respect to the geographic pole, a magnetic latitude of 60° corresponds to a geographic latitude of about 49° over North America, which is well within the mid-latitude wind systems of the stratosphere.

As a further development of this mechanism for ozone depletion, Reid et al. (1976) suggested that it might explain the mysterious correlation between extinctions and geomagnetic polarity reversals discussed above. This suggestion was based on two hypotheses: the increase in the global stratospheric area exposed directly to solar protons when the geomagnetic field disappears, and the probability that the Sun can generate flares much more intense than any we have yet seen, given the 1000 years or so occupied by a polarity reversal in comparison with the 20 years within which we have been observing solar-proton events. The area of the Earth lying at latitudes higher than 60° is about 13 percent of the total area, so that the total NO production would be increased by nearly an order of magnitude by removal of the geomagnetic field even if the events we have seen are the largest ever produced, which is unlikely. A flare 10 times more intense than that of August 1972 occurring during a polarity reversal would produce nearly 100 times as much NO as was produced by the August 1972 flare. The consequent ozone depletion might have serious consequences for living organisms, and might actually lead to extinction, especially in the case of organisms that might be suffering from other unrelated environmental stresses.

Figure 2 illustrates the magnitude of the ozone depletion expected throughout the stratosphere for solar-proton events of various intensities relative to that of August 1972, as well as for galactic cosmic rays (GCR), in the absence of the geomagnetic field. For comparison, the left-hand side of the figure shows a typical ozone profile. Figure 3 shows the height-integrated ozone depletion as a function of event intensity, indicating that the effect is very substantial, even for events not much more intense than that of August 1972.

The most obvious direct effect of ozone depletions on living organisms is an increase in the biologically effective ultraviolet radiation flux reaching them. An attempt to estimate this effect is illustrated in Fig. 4, which shows the relative effective UV dose experienced by an organism during a day at the equator. This was calculated by computing the UV flux reaching the surface as a function of wavelength, multiplying by a 'relative biological effectiveness' factor developed by Caldwell (1971) on the basis of the response of protein and nucleic acids to UV radiation, and summing over all hours of the day and all wavelengths. An event 10 times more intense than that of August 1972 occurring during a polarity reversal would increase the dose received by about 55% at the equator. The effect at higher latitudes

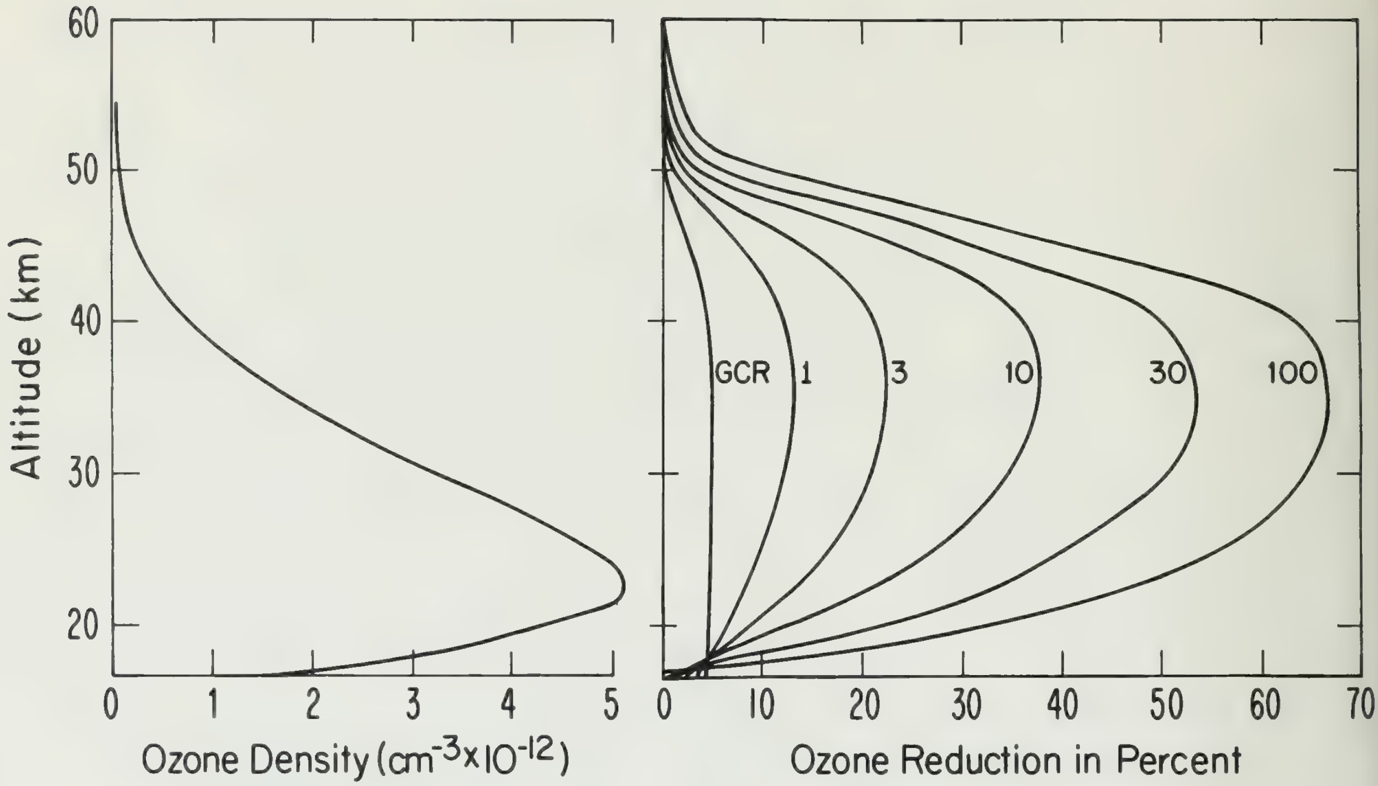

FIGURE 2. *Ozone depletion expected for solar-proton events during a geomagnetic polarity reversal. Intensities of the events are expressed in units of the event of August 1972 (after Reid et al. 1976).*

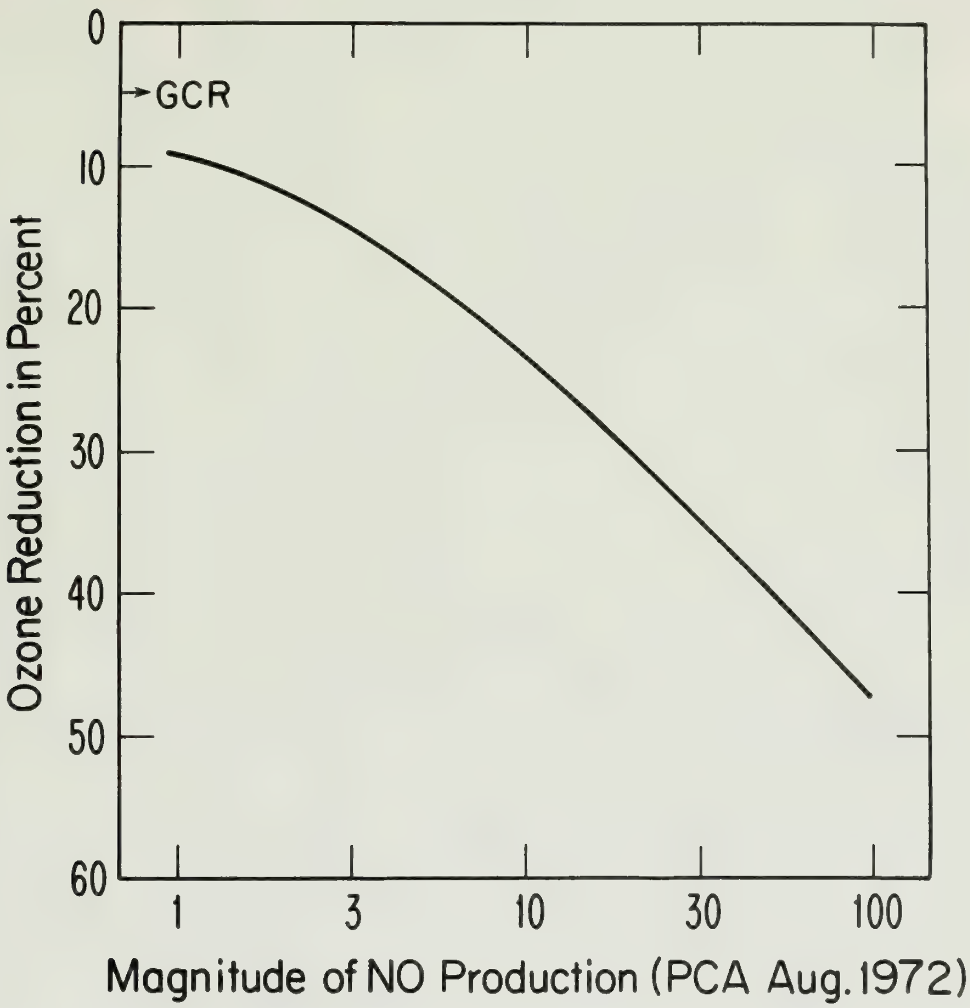

FIGURE 3. *Height-integrated ozone depletion as a function of event intensity (after Reid et al. 1976).*

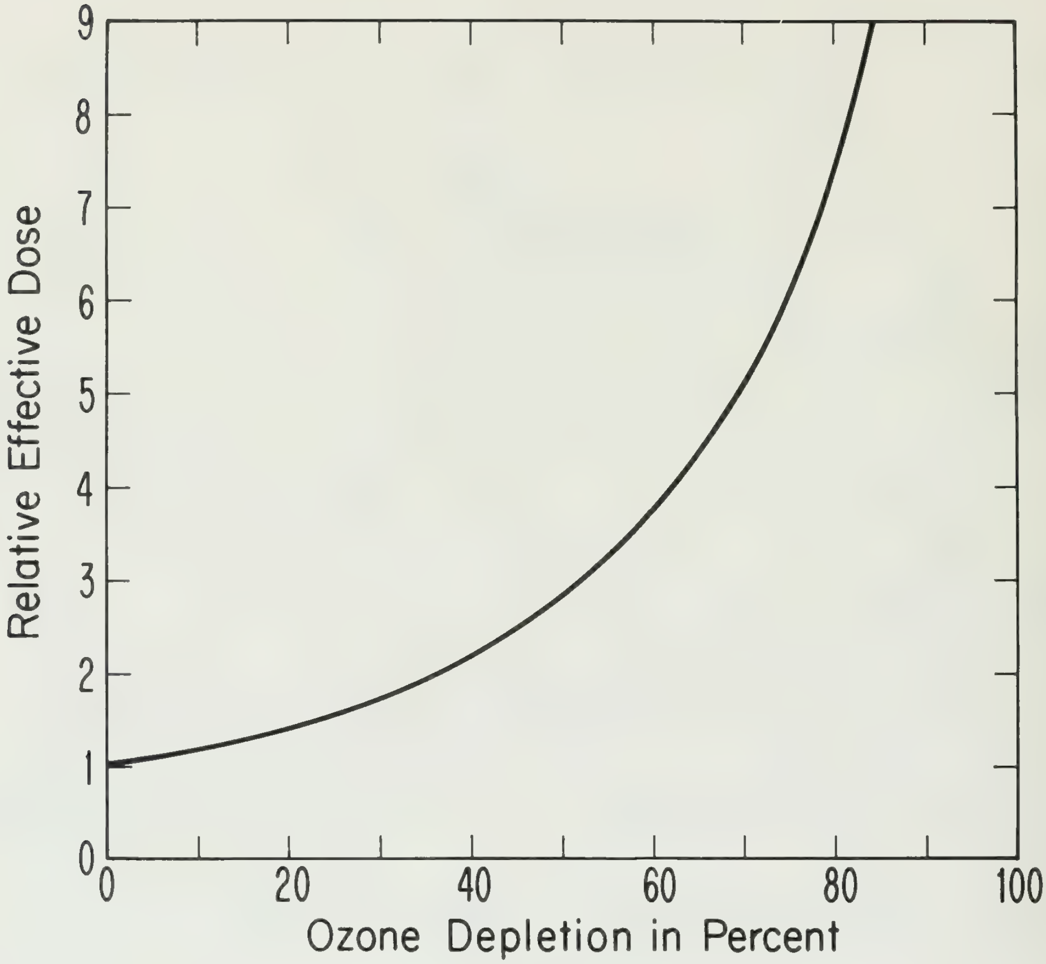

FIGURE 4. *Relative effective UV dose received at the surface of the Earth as a function of ozone depletion (after Reid et al. 1976).*

would be even larger, since the ozone content there is greater than at the equator, and present UV intensities are comparatively much lower.

A second potential effect of ozone depletions is climatic change, though this is difficult to express quantitatively at present. Figure 5 shows the changes in stratospheric heating rates expected for events of different intensities occurring during a polarity reversal. These are significant, and would lead to equally significant changes in the thermal structure of the stratosphere, which would in turn affect the radiation balance of the Earth. Changes in tropopause altitude might also be expected, changing the depth of the convective zone in the atmosphere and altering jet-stream characteristics. Our present understanding of the factors that determine global climate, however, is quite rudimentary, and it is not possible to carry such ideas much beyond the realm of speculation.

Having established a plausible mechanism for faunal extinctions accompanying geomagnetic polarity reversals, it seems natural to ask whether the same mechanism could have any bearing on the massive extinction catastrophes that have occurred in the distant past, the most recent of which took place at the Cretaceous-Tertiary boundary some 65 million years ago. Many theories have been advanced to account for this dramatic extinction event, among which the possibility of a supernova explosion in the galactic vicinity of the solar system has been widely discussed. Since the effects of a supernova and of a giant solar flare are rather similar in nature, at least as far as the atmosphere is concerned, it is possible to consider them together as simply different aspects of the same catastrophic event, i.e. an enormous increase in upper-atmospheric ionization rate. The chief difference lies in the time-scales — — in the case of a solar flare, the characteristic times are an hour for the electromagnetic (X-ray) radiation, and a day or two for the energetic particle fluxes; and in the case of a supernova, they are of the order of a month or two for the X-rays and a century or two for the particle fluxes.

In terms of ionizing radiation, the flare events of August 1972 produced some 6×10^5 erg cm^{-2} at the top of the polar stratosphere. If we adopt the

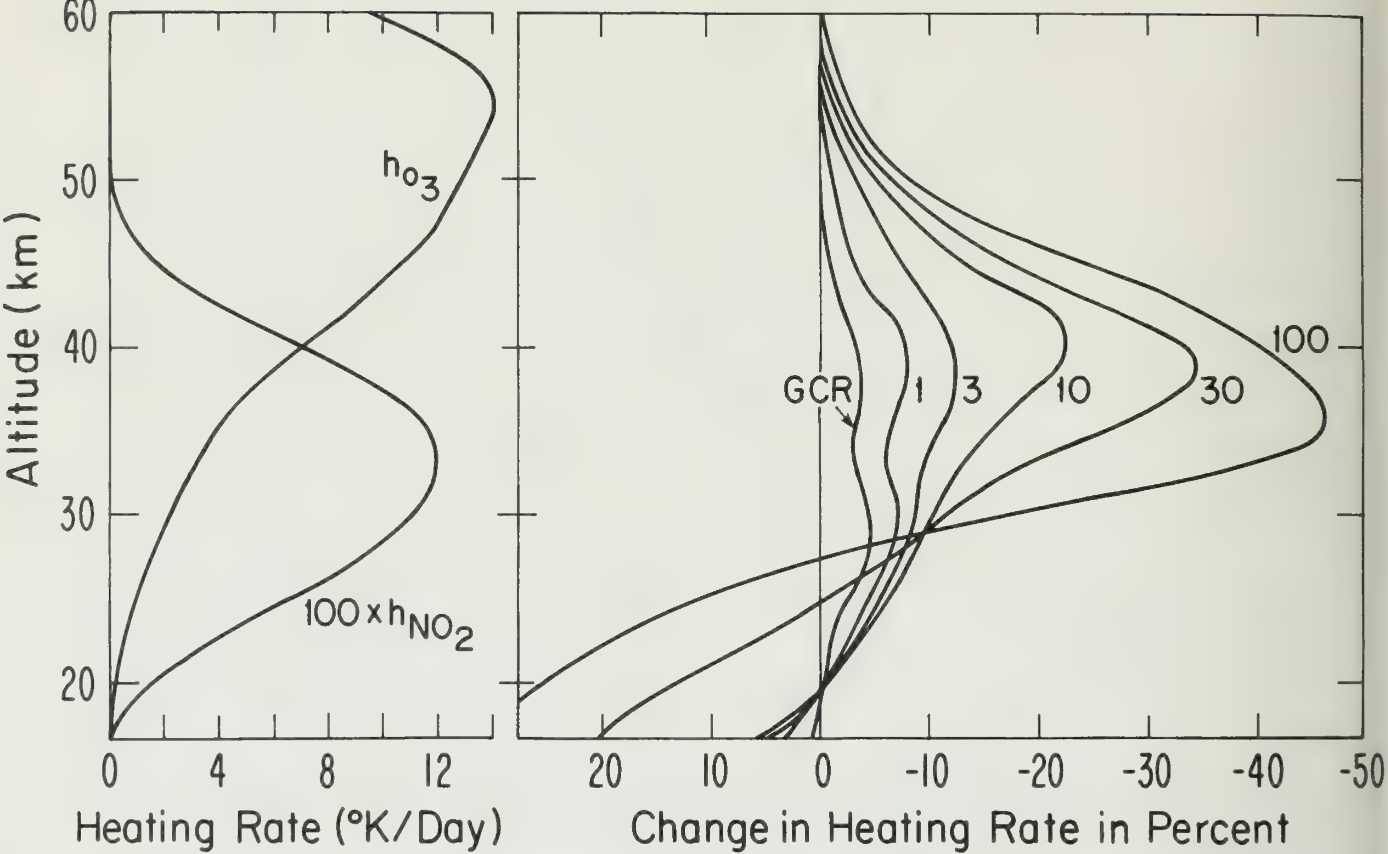

FIGURE 5. *Changes in stratospheric heating rates for events of various intensities occurring during a polarity reversal (after Reid et al. 1976).*

rather optimistic value of 10^{49} erg for the energy contained in the gamma-ray pulse from a supernova, we find that a similar energy influx would be produced at the Earth if the supernova were 300 parsecs distant. To attain an energy flux 1000 times larger than this would require either a solar flare event 1000 times more intense than that of August 1972, or a supernova explosion within about 10 parsecs. On the basis of the statistics of supernova explosions in other galaxies (Shklovsky 1968), it appears that supernova explosions within this distance may have occurred several times within the lifetime of the solar system, while the requirement for a flare 1000 times more intense than that of August 1972 may be placing too great a burden on the Sun as we know it today. Although the possibility that the Sun has gone through periods of very intense activity in the past cannot be ruled out, it appears that the supernova theory is the more likely of the two candidates. The possibility of severe ozone depletions resulting from supernova explosions has recently been discussed by Ruderman (1974) and Whitten et al. (1976).

When very large amounts of NO are created in the stratosphere, the scenario is probably quite different from that occurring after relatively small events, such as present-day solar flares. The ozone will be rapidly destroyed by the catalytic reaction pair discussed above, but in addition, as Crutzen and Reid (1976) pointed out, the three-body reaction

$$O_2 + 2NO \rightarrow 2NO_2$$

will take place rapidly enough to convert much of the NO into NO_2. At the higher levels, the NO_2 acts as a source of O atoms by photodissociation, and these O atoms in turn tend to re-form ozone. The NO_2 also screens out UV radiation, so that the UV levels at the surface might not become very large.

The climatic consequences of this chain of events, however, might be severe, and could possibly pose a serious hazard to living organisms. NO_2 has an absorption spectrum that is large throughout most of the visible part of the spectrum, and NO_2 column densities of the order of 10^{18}- 10^{19} cm^{-2} would lead to major decreases in the amount of solar radiation reaching the surface of the Earth, equivalent to a sharp decrease in the solar constant. Worldwide cooling and a decrease in global precipitation would probably follow, with disastrous consequences for the biosphere. The episode, however, would probably be relatively brief in duration (of the order of 10 years), though this might be extended somewhat by the reduction in precipitation, which forms the major sink for atmospheric odd-nitrogen. Most of the fixed nitrogen would eventually be deposited on the surface, where the great increase in nutrients could lead to some degree of eutrophication of fresh-water lakes. The atmosphere, however, would return to its normal state at the end of the episode. Animal species would probably suffer much more than plants, since seeds and spores could presumably survive the decade or so of adverse conditions, and could then germinate when conditions returned to normal. No such escape would be possible for those faunal species with low adaptability, however, and extinction would be a natural consequence.

Russell and Tucker (1971) postulated that a brief but severe climatic change might have been responsible for the Cretaceous-Tertiary extinctions, and that a supernova may have been the triggering mechanism. Although quantitative studies remain to be made, the above arguments certainly lend plausibility to their suggestion.

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Caldwell, M.M. 1971. Solar UV irradiation and the growth and development of higher plants, p. 131-177. *In* A.C. Giese [ed.] Photophysiology. Current topics in photobiology and photo chemistry. vol. 6. Academic Press, New York.

A review of published data on: 1) the results of artificial UV irradiation of higher plants; 2) actual terrestrial solar UV irradiation under various conditions of air masses and altitude; 3) responses of higher plants to filtered solar light; 4) defense mechanisms of higher plants against solar UV.

Crutzen, P.J. and G.C. Reid. 1976. Reply [to Béland and Russell 1976 - see Roy paper]. Nature 263:259.

The authors agree that the supernova model appears more probable than one involving a giant solar flare. A large cosmic event of that nature might produce colossal amounts of NO_2, which would perturb the radiation balance of the Earth and lead to rapid eutrophication.

Crutzen, P.J., I.S.A. Isaksen and G.C. Reid. 1975. Solar proton events: stratospheric sources of nitric oxide. Science 189:457-458.

Each of the recent large solar proton events produced a comparable or greater amount of stratospheric NO than the action of galactic cosmic rays over a year.

Hays, J.D. 1971. Faunal extinctions and reversals of the earth's magnetic field. Bull. Geol. Soc. Am. 82:2433-2447.

During the last 2.5 million years, eight species of widely distributed radiolarians became extinct isochronously throughout their range. Six of them disappeared in close proximity to magnetic reversals. The mass extinctions of marine and land animals at the close of the Paleozoic and Mesozoic eras coincide with a renewed reversal activity, after long intervals with few or no reversals.

Reid, G.C. and H.H. Sauer. 1967. The influence of the geomagnetic tail on low-energy cosmic-ray cutoffs. J. Geophys. Res. 72:197-208.

An attempt to relate the depression of low-energy cut-offs of solar protons to the permanent existence of a geomagnetic tail.

Reid, G.C., I.S.A. Isaksen, T.E. Holzer and P.J. Crutzen. 1976. Influence of ancient solar-proton events on the evolution of life. Nature 250: 177-179.

The authors suggest a mechanism by which solar protons might catastrophically deplete atmospheric ozone during a reversal of the Earth's geomagnetic field. Organisms would thereby be exposed to a harsher UV environment, particularly with a solar flare much more powerful than any observed to date. It is quite improbable that in the short period of our observations we have seen the most powerful flares possible.

Ruderman, M.A. 1974. Possible consequences of nearby supernova explosions for atmospheric ozone and terrestrial life. Science 184:1079-1081.

Hard X ray pulses or increased cosmic radiation originating in nearby supernova explosions may temporarily deplete the ozone layer. Terrestrial life would then be exposed to relatively huge solar UV flares every few hundred million years.

Russell, D.A. and W. Tucker. 1971. Supernovae and the extinction of the dinosaurs. Nature 229:553-554.

As the result of a nearby supernova explosion or a large solar outburst the atmosphere would absorb an enormous amount of energy. This would in a short time modify the entire circulation of the atmosphere. Long term effects would result from a change in albedo or the disruption of the ozone layer. This model is advanced to explain the rapid Cretaceous-Tertiary extinctions.

Shklovsky, I.S. 1968. Supernovae. Wiley, London. 444 p.

Standard textbook on observations of supernovae.

Uffen, R.J. 1963. Influence of the earth's core on the origin and evolution of life. Nature 198:143-144.

During a reversal of the Earth's magnetosphere there is a period of reduced or zero intensity of the dipole field. There should then be a great increase of cosmic radiation at the surface of the Earth, which is no longer shielded. Enhanced radiation levels will produce higher mutation rates, resulting in evolutionary discontinuity.

Whitten, R.C., J. Cuzzi, W.J. Borucki and J.H. Wolfe. 1976. Effect of nearby supernova explosions on atmospheric ozone. Nature 263:398-400.

The effects of a nearby supernova explosion on the ozone layer are significant and long lasting, but smaller than estimated by Ruderman (1974). Ozone depletion could extend over 10^3 - 10^4 years. The probability that such an event occurred near (5-10 parsecs from) the Earth within the past 10^8 years is about 1-5%.

VARIATIONS OF THE LUMINOSITY OF THE SUN AND "SUPER" SOLAR FLARES: POSSIBLE CAUSES OF EXTINCTIONS

Jean-René Roy

1. Introduction

The reasons for probing the Sun for the origin of the great catastrophic extinctions which hit the biosphere at the end of the Cretaceous are twofold. As opposed to a few years ago, we now realize how uncertain is our knowledge of solar structure and of the processes which keep it shining, and how unpredictable is its magnetic activity (Eddy 1976a). Moreover, contrary to the 'accidental encounter' required in the supernova hypothesis (Ruderman 1974, Whitten et al. 1976), the Sun has been 'up there', at the respectable distance of 1.5×10^{13} cm, near enough to become not only the source of life, but maybe at times the source of death (Reid et al. 1976).

In establishing the possible role of the Sun in triggering the great extinctions of the Cretaceous-Tertiary boundary or others, two scenarios come naturally under scrutiny. First, there is the likelihood of variations in the solar luminosity throughout the past history of our G2V star; these could have induced catastrophic climatic or atmospheric responses (increased storminess, drought, wet weather or a change in temperature). Second, solar activity could have been much more dramatic in the past and could have produced super flares, an order of magnitude more powerful than the events we have known in recent decades. Reid et al. (1976) and Béland and Russell (1976) have discussed the effect of such hypothetical giant flares on the biosphere.

Instead of speculating on whether or how the Sun might have killed the dinosaurs, I will rather point to important limitations in astronomical observations and theoretical calculations. My approach is justified, because these limitations severely restrict the relevance of extrapolation. It is important to be well aware that we do not understand the luminosity of the Sun and its magnetic and flaring activity.

2.1 Variations Of The Luminosity Of The Sun

Stable standard models of the Sun which describe the structure, the properties and the energy output of our star using the best knowledge of contemporary physics, assume that the surface luminosity balances the luminosity of the core; energy is generated through thermonuclear fusion of hydrogen in the central nucleus. Reactions, which convert four hydrogen atoms into one helium atom, are assumed to proceed at a steady rate releasing secondary fusion products, photons and two neutrinos. Change in the surface luminosity supposedly arises from the depletion of hydrogen and the build-up of helium. The nuclear time scale of change in the luminosity is of the order of 10^9 years compared to 3×10^7 years for the gravitational time scale $t = GM^2/RL_\odot$. Other relevant time scales are the 5-min oscillation of the photosphere, the 11-year sunspot or 22-year magnetic cycles of global circulation in the convective envelope, and the 1-10 day period of the convective turnover. Finally, there is the thermal cooling time of 2×10^4 years; change of the convection efficiency, e.g. by a strong magnetic field, in a time shorter than 2×10^4 years would alter the luminosity.

TABLE I: *THE SUN: PHYSICAL PARAMETERS (after Allen 1973)*

Radius	$R_\odot$	$= 6.9599 \times 10^{10}$ cm
Mass	$M_\odot$	$= 1.989(2) \times 10^{33}$ g
Mean density	$\bar{\rho}_\odot$	$= 1.409$ g cm^{-3}
Gravity of surface		$= 2.7398(4) \times 10^4$ cm s^{-2}
Radiation emitted	$L_\odot$	$= 3.826(8) \times 10^{33}$ erg s^{-1}
Angular momentum (based on surface rotation)		$= 1.63 \times 10^{48}$ g cm^2 s^{-1}
Rotational energy (based on surface rotation)		$= 2.4 \times 10^{42}$ erg
Magnetic flux from whole Sun		$\approx 10^{23}$ maxwell
Distance from ⊕		$= 1.495979(1) \times 10^{13}$ cm
Sun as a Star		
Age		$= 5 \times 10^9$ yr
Colour Index B-V		$= + 0.65$
Spectral type		= G2V
T_{eff}		$= 5770$°K
Absolute M_V		$= +4.83$
Apparent m_V		$= -26.74$

2.2 The Problem Of The Young Sun

Following the conventional view, we are faced with the disturbing prospect of a young Sun with a much lower luminosity. Indeed the best standard solar models predict that the luminosity of the Sun should have increased 30% from the assumed time of formation 4.7×10^9 years to the present, i.e. about a 1% increase per 50 million years (Ulrich 1975). Assuming no self-adjusting mechanism in the Earth's atmosphere, what would have happened to the Earth's climate under a $L_{young} = 0.75\ L_{now}$? Would the oceans have frozen over? From the works of Sellers (1969) and Budyko (1969), once the earth is frozen it is unlikely to melt because the albedo of ice and snow is higher than that of water. The disturbing evidence is that liquid water has been with us for as long as 3×10^9 years. The Earth did not freeze; instead we are presently (last 2 million years) suffering from one of the coldest periods in the Earth's history. The prediction of a young Sun of low luminosity points to a possible serious discrepancy between theory and observations. Perhaps a blanketing atmosphere similar to that of Venus compensated for the lower solar flux. This stresses the need for a comparative study of the paleoclimates of Mars and Earth to disentangle solar from local influences.

2.3 The Missing Neutrinos

As seen earlier, neutrinos should be emitted by the Sun from the nuclear reactions taking place in its core. However, despite intensive efforts by Davis and his co-workers (see Bachall and Davis 1976) these neutrinos have not yet been detected. The discrepancy between predicted and observed measurements is such that the theory of stellar evolution is challenged in its basic premises. More sophisticated experiments and improved theoretical calculations of nuclear reaction rates and of the radiative opacity of matter have only seemed to deepen the gap between theory and observations. Therefore nuclear reactions may not be currently sustaining the luminosity of the Sun (Ulrich 1975).

To solve this puzzle, suggestions have been made ranging from a central black hole (Clayton et al. 1975) which provides half the energy at the center, to various instabilities (Fowler 1972). Ulrich (1975) has recently shown however that rapid intermittent mixing of the solar core, such as proposed by Dilke and Gough (1972), is unlikely to be the reason for the failure to detect neutrinos; moreover the required fluctuations in the solar luminosity of 10% in the span of the last 10^6 years, if accompanied on Earth by appropriate temperature changes, are clearly at variance with paleoclimatic data.

2.4 Magnetic Field And Convection

Eddy (1976b) has studied the behaviour of solar activity during the past 5000 years by comparing the rate of ^{14}C formation, the naked-eye sunspot historical records, aurorae and sunspot numbers. Solar activity has been neither constant nor regular. Instead, there have been successive periods of intense activity interposed with century-long periods when the Sun displayed little or no sunspot activity. The most recent such period was the Maunder Minimum from 1645 to 1715, as shown in Fig. 1 from Eddy (1976b). If such fluctuations are present over the last few millenia, it is reasonable to expect much more drastic excursions in the level of solar magnetism during the lifetime of the Sun. The magnetic field could indeed alter the efficiency of the energy transported through the solar envelope, where the dominant mechanism is convection. The intensification of the magnetic field could change the mixing-length parameter ℓ/H; H is the pressure scale height and ℓ represents roughly the distance required by hot rising bubbles to dissolve smoothly into the surroundings, delivering any excess energy they possess or absorbing any deficiency. Ulrich (1975) has calculated a solar model with a changing ℓ/H, modifying the rate of energy flow through the convective zone. Accordingly, the energy content of the zone is altered, causing the model to expand and contract. The response of solar luminosity to a change in convective efficiency in a time scale less than 2×10^4 years is

$$L - L_{av} \approx 3 \times 10^4 \frac{d(\ell/H)}{dt} ,$$

where L and L_{av} are the instantaneous and average luminosities, ℓ/H is the

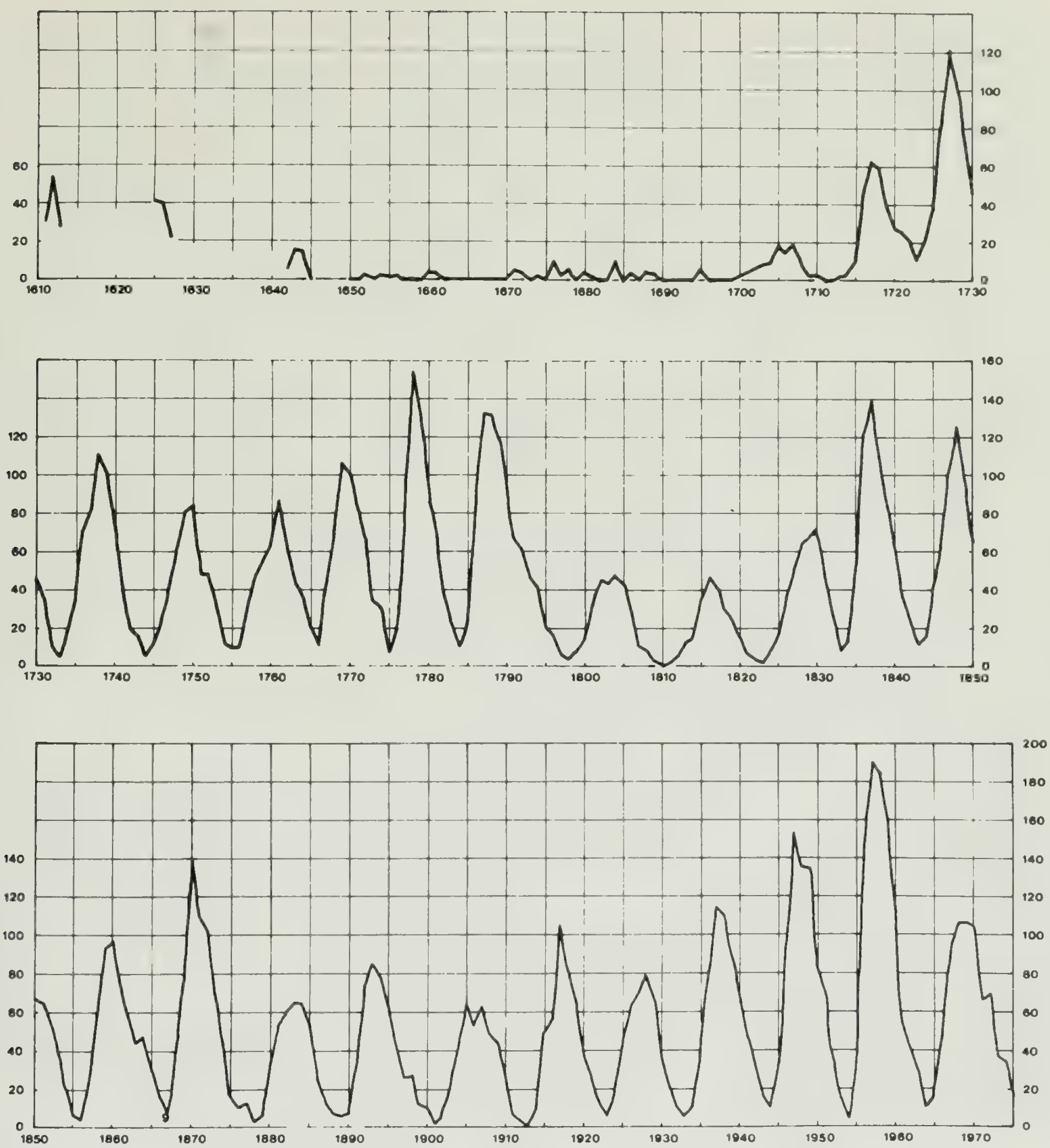


FIGURE 1. *The sunspot number relating to the level of solar activity is plotted from year 1610 to present. The period from 1645 to 1715 corresponds to the Maunder Minimum when solar activity was remarkably low (courtesy of J.A. Eddy).*

mixing-length (generally accepted value 1.5) and t is time in years. If we suppose that the magnetic field changed ℓ/H by 0.5% in 3000 years, a change of 5% in luminosity would ensue; the radius would change only at a rate of $10^{-5}\ R_\odot\ yr^{-1}$.

However this suggestion has absolutely no bearing on the neutrino problem if we accept $\Delta L/L < 5\%$ from geophysical data. For the neutrino flux to be lowered we must assume that the core luminosity = L_{av} is 80% of present solar luminosity. The present Sun would be 20% brighter than average. Unless the terrestrial atmosphere contains a rigorous self-adjusting mechanism, this variability is incompatible with paleoclimatic data. Disregarding the ineluctable neutrino problem, we can envision an increased magnetic activity which, by lowering solar luminosity, would subject the Earth to tremendous environmental stresses. On the Sun larger activity centers and field strengths would boost solar activity and the energy of the flares produced.

2.5 Evidence For Variations Of $L_\odot$

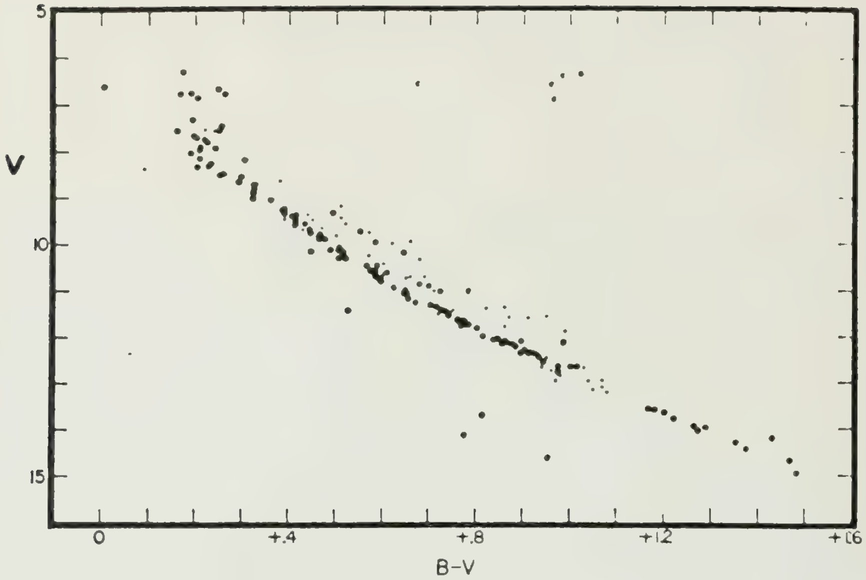
The amount of solar radiation reaching the top of our atmosphere is called the solar constant and is known within 1% to be $1.358 \times 10^6\ erg\ cm^{-2} s^{-1}$. Labs and Neckel (1971) have shown that short-term fluctuations of the solar constant over a few years are small and have no trend; in terms of $L_\odot$, the standard deviation of the various measurements is 1.8% or $0.025 \times 10^6\ erg\ cm^{-1} s^{-1}$ (Smith and Gottlieb 1974). The 30-year measurements by Abbot et al. (1942) at the Smithsonian Astrophysical Observatory reveal an amplitude of 1-2% mainly due to a drop during the mid-1920s. Long-term variation is associated with the problem of ice ages and climatic variations on Earth, some of which are probably due to variations in the Earth's orbital parameter (Milankovitch 1930). In a simplistic view which assumes a constant cloud cover (Budyko 1969, Sellers 1969) every 1% change in luminosity translates into a change of 2°K on Earth. Again, any change in the Earth's temperature should be compared with Martian paleoclimatic data.

As suggested by Sagan and Young (1973), long-term luminosity variations are unlikely to be restricted to the Sun. Open star clusters, which are rather homogeneous assemblages of stars, represent a good testing ground for establishing the limit of $\Delta L/L$. The stars in a cluster are roughly at the same distance, and of the same age and chemical composition. Accordingly, their temperatures and apparent magnitudes should be very tightly correlated in the Hertzsprung-Russell diagram. The low luminosity end of the Praesepe cluster colour-magnitude diagram is crowded with stars still in their hydrogen burning phase. The scatter in the low luminosity main sequence should be representative of observational errors. The main sequence line for the Praesepe cluster given by Johnson (1952) in Fig. 2 is indeed very narrow. In the region where solar type stars are found (B-V = +0.65) the width of the main sequence band is 10-20% in luminosity. Thus the spread in main sequence luminosities in the Preasepe cluster is consistent with a 10% variation in the solar luminosity.

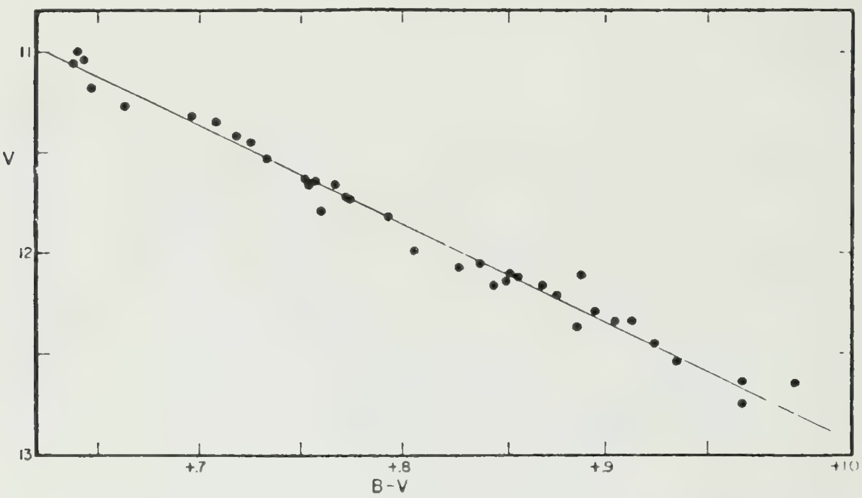
3.1 Super Flares From The Sun

Solar flares represent the most energetic transient events taking place in the solar system. The energy released from a flare starts in a few seconds, reaches its maximum in matters of minutes and decays for days. Švestka (1975) has reviewed observations and theories of flares in a recent monograph. Zirin and Tanaka (1973) have given an excellent description of some aspects of the powerful flares of August 1972. Mitra (1974) has discussed extensively the effects of solar flares on the Earth's atmosphere.

Let us concentrate our attention on the most energetic type of events. The flare appears as an intense sudden flash of radiation over the whole electromagnetic spectrum (gamma, X-ray, ultraviolet, visible, radio) originating from a region of a large scale, strong but unstable magnetic field, normally associated with sunspots (Fig. 3). Figure 4 shows a large solar flare observed in the emission line of hydrogen Balmer α showing the effect on the chromosphere. Figures 5 and 6 display the X-ray and proton events accompanying some solar flares. Knowing the irregularities of solar activity in the recent past, one would be however foolhardy in extrapolating the 11-year cycle back



V versus *B–V* for Praesepe. The large dots represent photoelectric observations, while the small dots represent values transformed from the work of Haffner and Heckmann.



V versus *B–V* for the narrowest portion of the Praesepe main sequence

FIGURE 2. *Hertzsprung-Russell diagram of the Praesepe open cluster. Visual magnitudes (V) of the individual stars are plotted against their colour (B-V). The Sun has a B - V = +0.65. The width of the main sequence of Praesepe stars in that portion corresponds to a 10-20% range in their luminosity. (from H.L. Johnson 1952).*

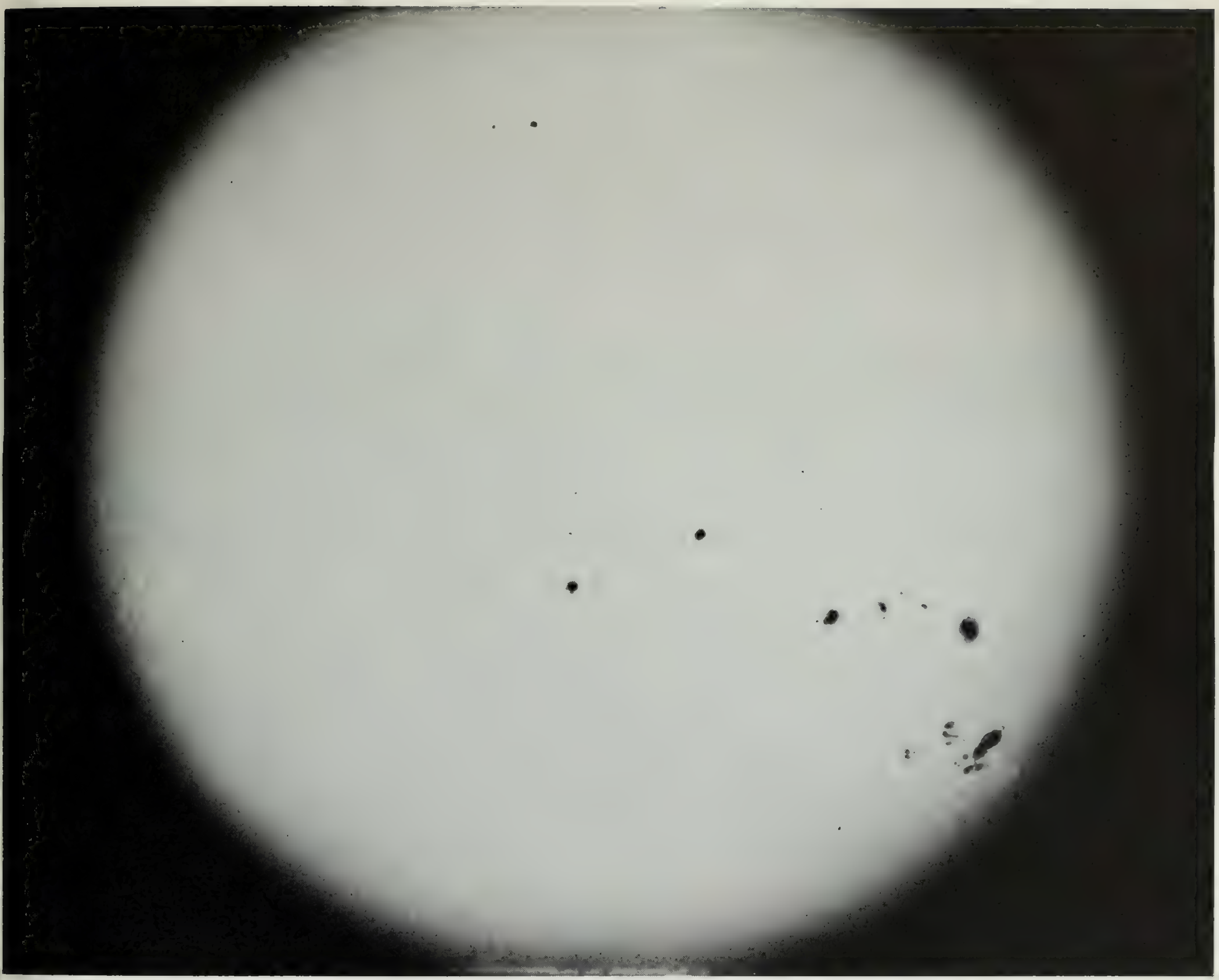


FIGURE 3a. *The solar disk with sunspots at a time of mild solar activity (courtesy of Sacramento Peak Observatory).*

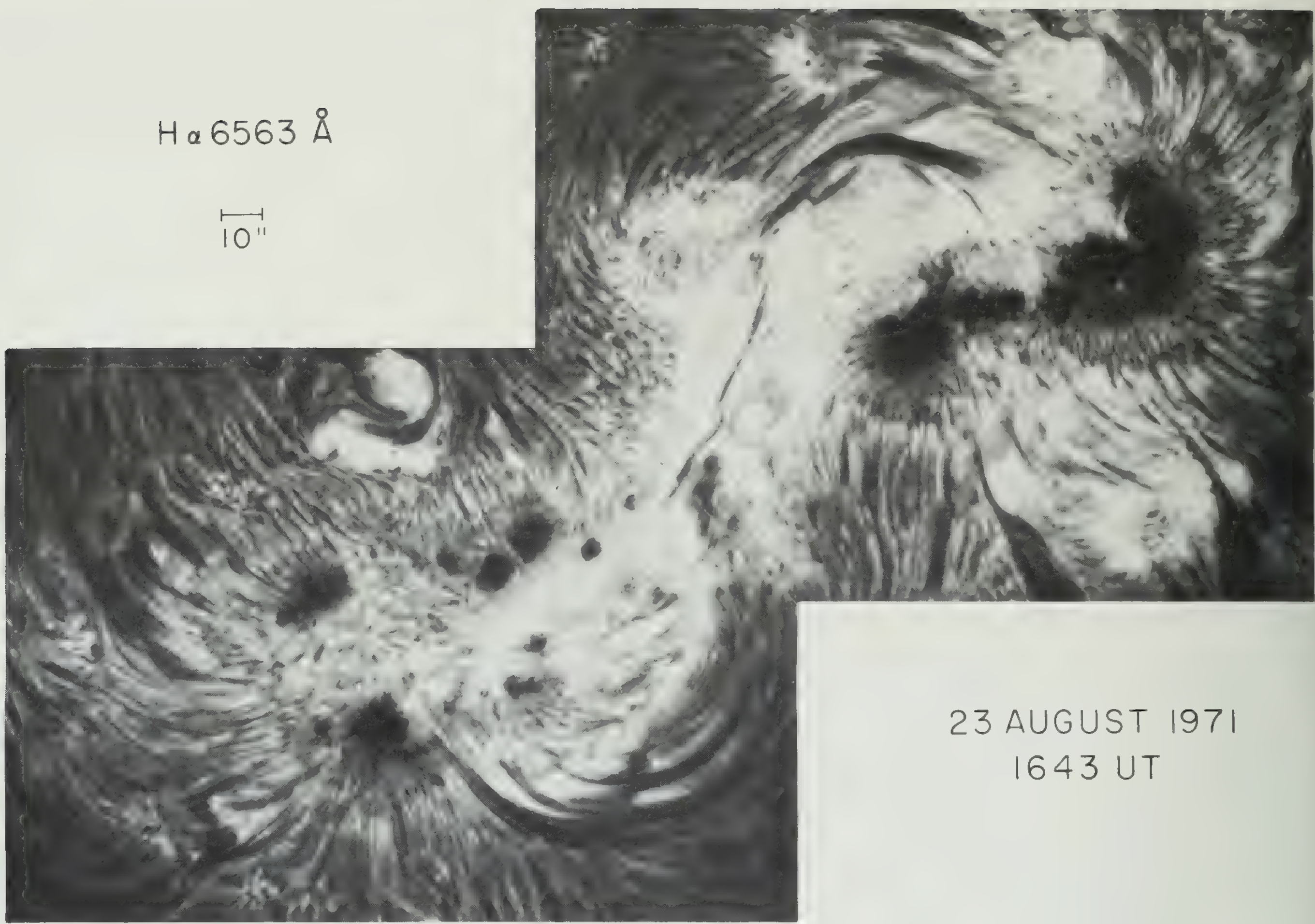


FIGURE 3b. *A large sunspot group photographed in the light of hydrogen Hα 6563 Å with the solar tower telescope at Sacramento Peak Observatory. Ten seconds of arc correspond to about 7200 km on the Sun.*

FIGURE 4. *A medium-sized but energetic solar flare photographed in the light of Hα 6563 Å at the Ottawa River Solar Observatory during the period of minimum solar activity on 28 March 1976. The edge of the photograph is equivalent to approximately 150,000 km (courtesy of Vic Gaizauskas, HIA).*

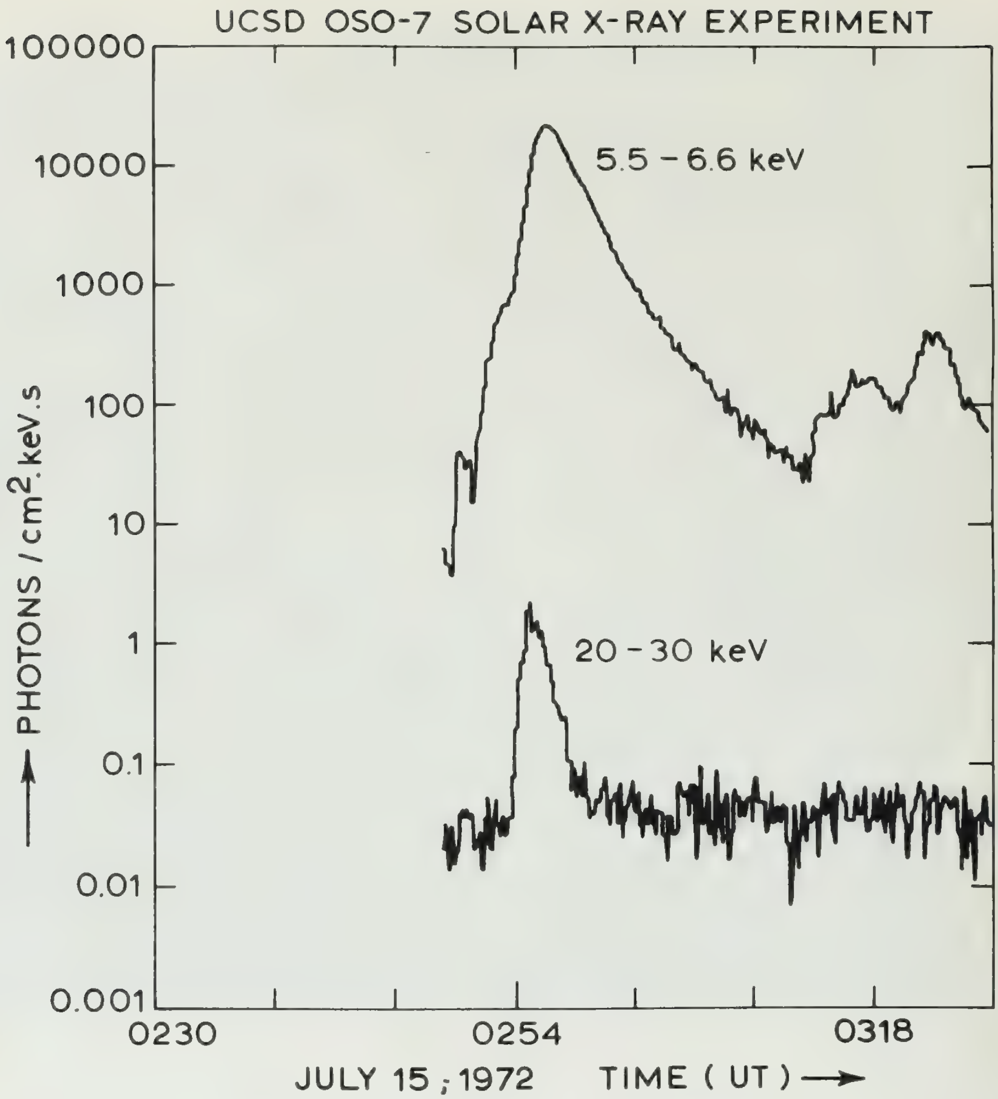


FIGURE 5. *A typical X ray burst profile accompanying a solar flare behind the limb of the Sun on July 15, 1972. Most of the X ray flux however is at lower energies than displayed here.*

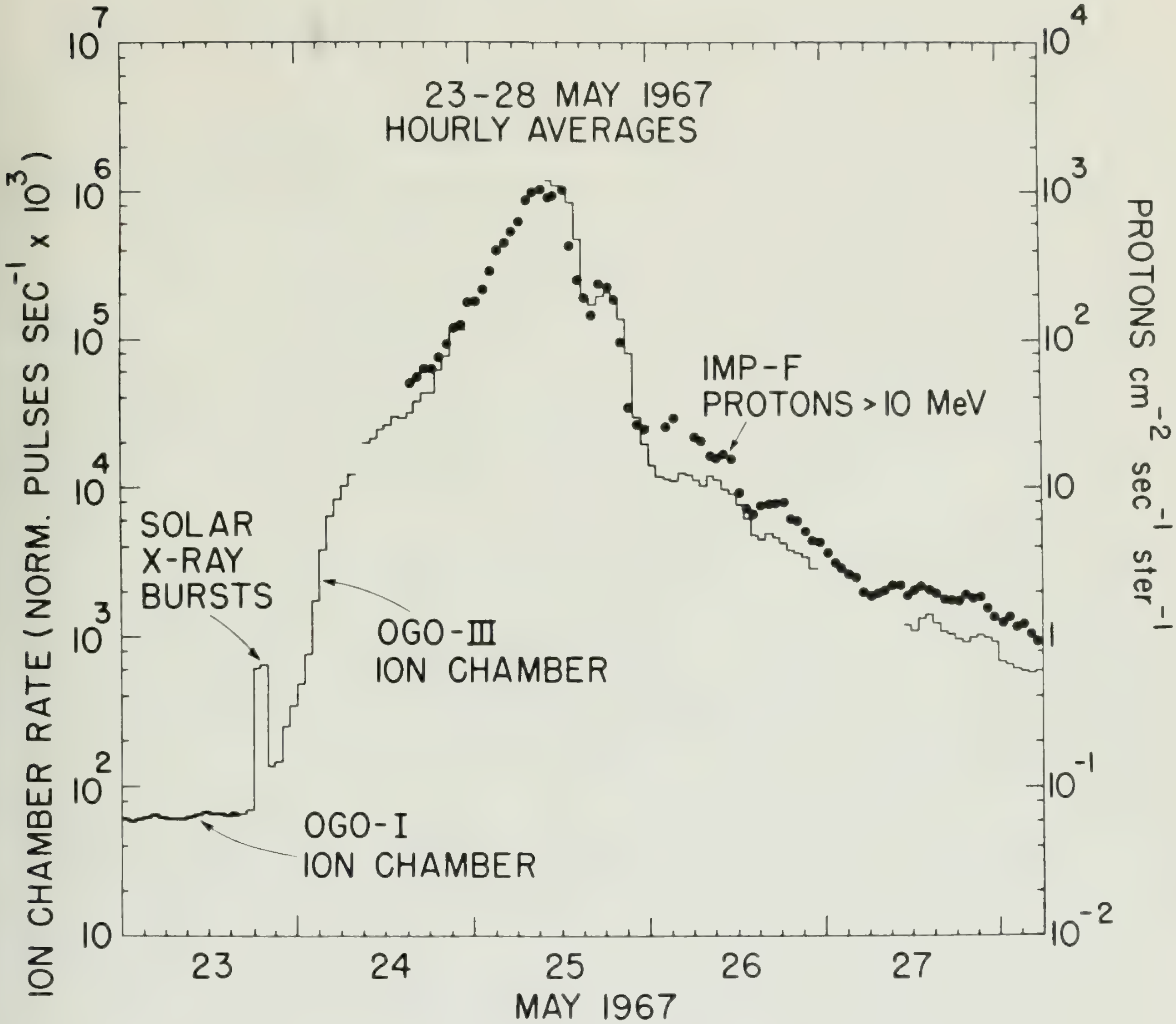


FIGURE 6. *A very large solar flare visible in continuum light took place on 23 May 1963 at 1800 UT (cf. spike in X rays). The flare was followed by a large proton event which lasted many days (from C.O. Bostrom, D.J. Williams and J.F. Arens. 1968. ESSA Solar Geophys. Data, IER-FB-282: 156).*

to the beginning of the Sun. It would also be surprising to have witnessed in recent years the largest solar flares in the whole history of the Sun. Statistically, this is more unlikely.

Table II lists the estimated energy released and its distribution in a large current flare. The soft X rays, the ultraviolet radiation and the penetrating protons, have the most significant impact on the terrestrial environment. Table III lists the relevant parameter of these fluxes at a distance of 1 A.U. = 1.5×10^{13} cm. Energetic protons have important and long lasting effects on the Earth's atmosphere. Proton events can destroy the ozone layer, modify the atmospheric thermal balance and induce climatic changes through change in the opacity and albedo of the atmosphere (Reid et al. 1976, Crutzen et al. 1976, Frederick 1976).

The fundamental question remains: can the Sun generate cataclysmic flares up to 10^4 times more powerful than the events we are familiar with? Unfortunately, unless ancient cosmic explosions left their signatures in lunar rocks, we can only speculate on flare activity in the remote past.

3.2 Stellar Flares And Solar Flares

What do other stars tell us? A group of red dwarf stars, called UV Ceti flare stars, are characterized by the presence of energetic events very similar in their spectral properties to solar flares (Kunkel 1975, Moffet 1974, Lacy et al. 1976). Although many orders of magnitude fainter than the Sun, these stars produce flares equal and even many times more powerful than the largest solar flares. The mean energy per flare increases with increasing quiescent energy of the parent star. Also the mean rate of the energy loss due to flaring increases with increasing quiescent energy. Expressed as a fraction of the quiescent energy, however, the rate of energy loss due to flaring decreases with stellar brightness; this is due to the strongly decreasing frequency of flaring as a function of quiescent energy. Events become less frequent in brighter stars. Somewhere between the quiescent energy of 10^{30} erg s^{-1} and 10^{33} erg s^{-1} (solar luminosity), these relations must

TABLE II. *ENERGY RELEASED IN A LARGE SOLAR FLARE*

Visible	Balmer α line emission	3×10^{30} erg	10^{31} erg
	All line emission	6×10^{30}	
	Continuum emission	1×10^{30}	
High-energy	UV emmission (20-1400 Å)	$> 10^{32}$	
	Soft X rays (1-20 Å)	1.5×10^{31}	
	Hard X rays & gamma rays	10^{29}	
	Protons ($E > 10$ MeV)	$> 10^{31}$	
	GLE ($E = 1$ to 30 GeV)	3×10^{30}	
Mechanical	Visible ejection	10^{31}	
	Interplanetary shock wave	10^{32}	
	Total energy	2.5×10^{32} erg	

TABLE III. *ENERGETIC RADIATION FLUX AT EARTH FROM A SOLAR FLARE*

	erg $cm^{-2}s^{-1}$	Duration
Soft X rays (1-20 Å)	1	1 hr
Extreme UV	10^2 - 10^3	100 - 1000 sec
Protons > 10 MeV	$> 5.6 \times 10^{-2}$ erg $cm^{-2}s^{-1}str^{-1}$	10 hr
Cosmic rays (1-30 GeV)	0.3	1 hr

TABLE IV: *ENERGY FROM WHITE-LIGHT FLARES*

	DATE	TIME UT	AREA CM^2	CONTRAST $\Delta I/I$	ESTIMATED ENERGY erg	ESTIMATED OUTPUT $erg\ s^{-1}$
a.	1.9.1859	1118-1124	4×10^{18}	$\sim 20\%$	$\geq 9 \times 10^{30}$	$\geq 3 \times 10^{28}$
b.	5.3.1946	1124-1127	6.7×10^{18}	$\geq 10\%$	$> 5.9 \times 10^{30}$	$> 2 \times 10^{28}$
c.	23.2.1956	0345-0350	1.73×10^{18}	$< 10\%$	$< 2 \times 10^{30}$	$< 7 \times 10^{27}$
d.	23.5.1967	1838-1845	8.72×10^{17}	16%	2.2×10^{30}	5.3×10^{27}
e.	7.8.1972	1519-1524	5.9×10^{17}	50%	5.8×10^{29}	6×10^{27}
f.			2.08×10^{17}	11%	4.0×10^{29}	8.9×10^{26}
g.	4.7.1974	1356-1358	1.2×10^{17}	35%	1.97×10^{29}	1.64×10^{27}

a. Carrington & Hodgson 1859
b. du Martheray 1946
c. Notuki et al. 1956
d. De Mastus and Stover 1967
e.f. Rust and Hegwer 1975
g. Feibelman 1974

break down, since they predict that the Sun should have flares with a mean energy per flare of 4 x 10^{35} erg in the continuum; this is at least three orders of magnitude more powerful than any observed. Table IV shows the continuum energy released during some of the rarely observed white-light flares on the Sun; the average continuum emission of a large solar flare is about 6 x 10^{30} erg at an output rate of 10^{28} erg s^{-1}.

Although flare stars refer to red dwarfs up to a spectral type as early as dK7e, flares have been reported on early-type stars (Andrews 1964, Ludendorff and Eberhard 1905, Bakos 1969, Page and Page 1970, Eggen 1948, Philip 1968). However these flares differ in important aspects from those of the Sun and dMe stars. A large flare on the Sun produces 10^{32} erg at a rate of 10^{29} erg s^{-1}; a large flare on a dMe star produces a peak flux of 10^{32} erg s^{-1} with a total energy output of 10^{35} erg. The peak flux reported by Bakos (1969) and Page and Page (1970) were approximately 10^{39} erg s^{-1} and 10^{37} erg s^{-1}. Flare activity among certain W Ursae Majoris stars is similar to that of dMe stars in several respects: duration, spectral energy distribution, light curves (Kunkel 1975).

4. Summary And Conclusions

a) Short-term variation in the luminosity of the Sun is found to be less than 1%. Astrophysical observations of solar-type stars in open clusters are consistent with a long term variation of 10%.

b) A large-scale build-up of the solar magnetic field would produce a drop in solar luminosity by affecting convective efficiency; it would increase flare activity and the mean energy per flare.

c) The largest flares currently release an energy of a few times 10^{32} erg. Stars many orders of magnitude fainter than the Sun are found which produce flares much more powerful than does the Sun. From their behaviour the Sun might be expected from time to time to produce flares with $>10^{35}$ erg. A condition would be magnetic field strengths up to three times higher than found in present sunspots and emitting area 100 times bigger than for present flares, implying very large sunspots covering 4% of a solar hemisphere; this would provide a reservoir of magnetic energy 1000 times greater.

5. Future Work

a) Comparative study of paleoclimates on Mars and Earth to sort out direct solar effects from local ones.

b) Search for ancient giant flares by studying tracks left in lunar rocks by solar cosmic rays.

c) Observation of solar-type stars for flare activity.

d) Solution of the "missing neutrino" problem; construction of non-standard variable luminosity models of the Sun.

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THE EFFECT OF A NEARBY SUPERNOVA EXPLOSION ON THE CRETACEOUS-TERTIARY ENVIRONMENT

Wallace H. Tucker

In the past two decades astronomy has undergone what has been called a high energy revolution. The new disciplines of radio and X ray astronomy have developed and with them a growing realization that our universe is one in which violence is the rule rather than the exception. We now know that stars and even galaxies are wracked by explosions that produce high energy particles and radiation at rates far in excess of that in normal stars and galaxies.

The high energy revolution has radically changed the astronomer's view of the universe and has led to the acceptance of some bizarre physical concepts such as neutron stars and black holes. The question before us today is whether it will also bring about a change in our thinking in other disciplines. To be specific, can a cosmic catastrophe, such as a supernova explosion, have had an effect on the evolution of life on Earth? Even more specifically, could a nearby supernova explosion have triggered the widespread faunal extinctions which are associated with the Cretaceous-Tertiary boundary? Schindewolf (1954) was among the first to suggest this possibility.

The cause of a supernova outburst is still the subject of intensive investigation and considerable controversy (Lamb and Pethick 1976, Wheeler 1973), but it is generally agreed that the onset of the explosion is ultimately related to instabilities in the structure of the star that arise when the supply of nuclear fuel in the central parts of the star is exhausted. These instabilities occur only in stars whose mass is greater than about one and a half times that of the Sun. Less massive stars, such as the Sun, begin to contract when their nuclear fuel is consumed. Ultimately the pull of gravity is balanced by the pressure of "degenerate" electrons: an incompressible electron fluid that finally emerges because no two electrons can occupy the same energy state. When this stable configuration is reached, the star has become a white dwarf and slowly dies "not with a bang but a whimper." In the case of stars whose mass exceeds about 1.5 solar masses at

FIGURE 1. *Photograph of a supernova in the galaxy NGC 5253, taken in May, 1972 ($\frac{1}{2}$ hour exposure). The supernova is outshining the galaxy in which it is located (courtesy of Christine Clement, University of Toronto).*

FIGURE 2. *Photograph of the same supernova as in Fig. 1, taken in July, 1972 (3 hour exposure). The supernova has faded but the galaxy is better defined in the longer exposure (courtesy of Christine Clement, University of Toronto).*

the end of their helium burning phase, the density and temperature in the central core exceed the critical values beyond which stability is possible. Then the star collapses under the influence of gravity and an explosion ensues.

For almost two weeks the exploding star - a supernova - radiates more energy than a billion suns and ejects matter at close to the velocity of light (Figures 1, 2). Cosmic rays (the nuclei of hydrogen and other light elements) are probably produced in abundance and elements heavier than iron are thought to be synthesized during the first few seconds of the explosion itself. These heavy elements, along with those manufactured earlier by the star during its lifetime, are ejected into interstellar space to become part of a cosmic reservoir that supplies the raw material for new stars and planets (Figure 3). Quite likely most of the matter of which we are made was originally part of the debris of supernovae.

The expanding shell of debris creates a nebula that for hundreds or even thousands of years radiates vigorously in both the X ray and radio regions of the spectrum (Figures 3, 4, 5). In addition the cataclysm may leave behind a small, extremely dense core. The discovery of pulsars suggests that this core, rotating at high speed, can be a pulsating source of radiation.

About one star in 100 produces a supernova. Since a supernova explosion is a rare event within any one galaxy, the only way its initial phases can be studied is by monitoring many galaxies. In this way about a dozen supernova outbursts per year are observed (Figures 1, 2). Taking into account the number of galaxies observed, one obtains an estimate of about one supernova per 50 years for a galaxy such as ours (Tamman 1970). An analysis of historically observed supernova explosions in our galaxy yields a similar estimate (Tamman in press).

One of the first major discoveries of radio astronomy was that high energy particles are produced in the expanding shells of supernova remnants for as long as a thousand years after the explosion (Shklovsky 1968, Woltjer 1972, Ginzburg and Syrovatskii 1964). This means that a sizeable number of

FIGURE 3. *The Crab nebula about 2 kiloparsecs away is a relict of the supernova event of 1054 A.D. recorded in the Sung-Shih astronomical annals of China. It was recorded as a new star, or* guest star, *and was first seen on July 5 or 6. It was bright enough to be seen in the daytime for about three weeks, and then slowly faded in brilliance.*

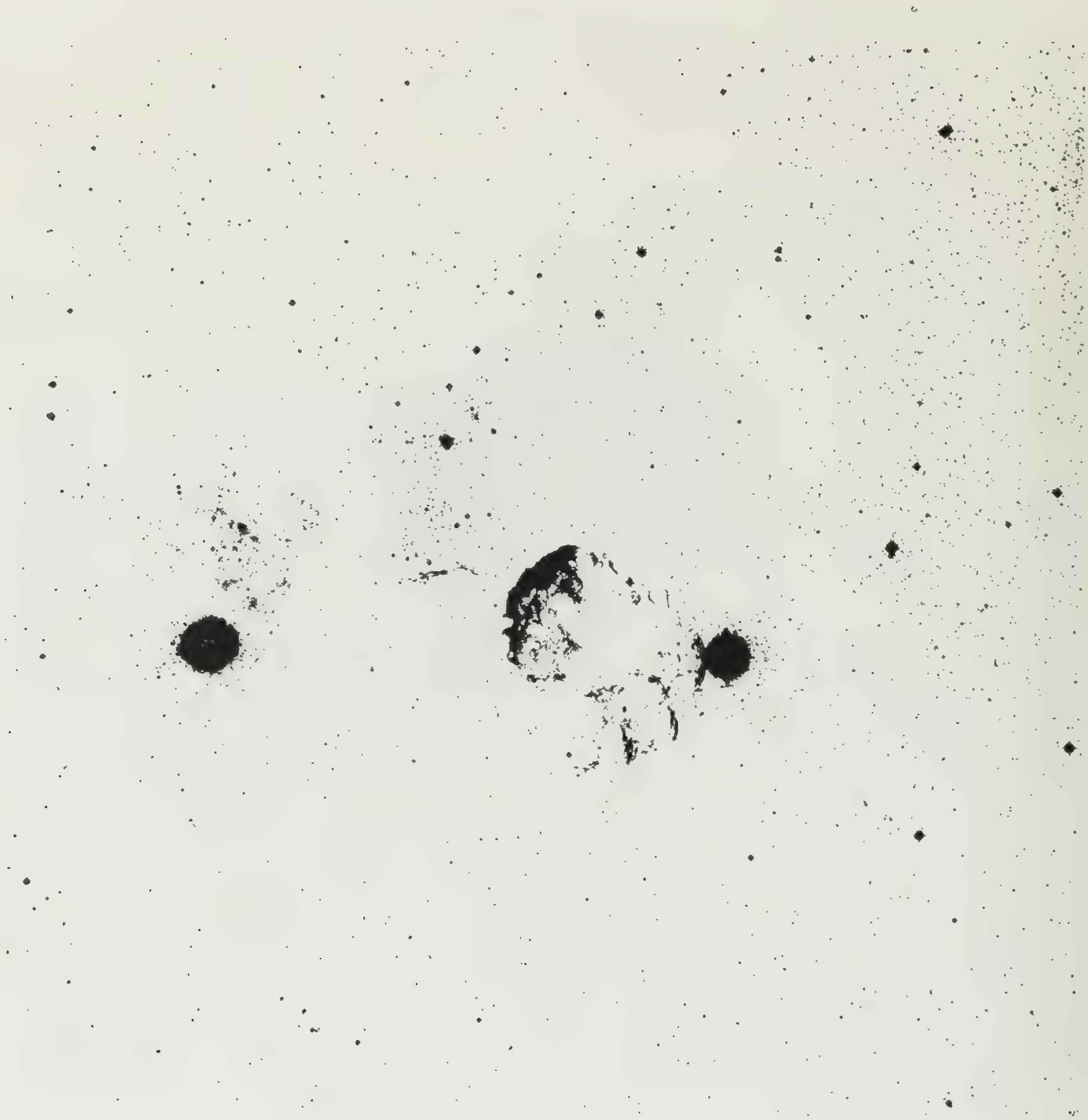

FIGURE 4. *The nebula IC443 in the constellation of Gemini is an old supernova remnant (SNR). It is postulated to be the remnant of a Type II supernova event which occurred several tens of thousands of years ago.*

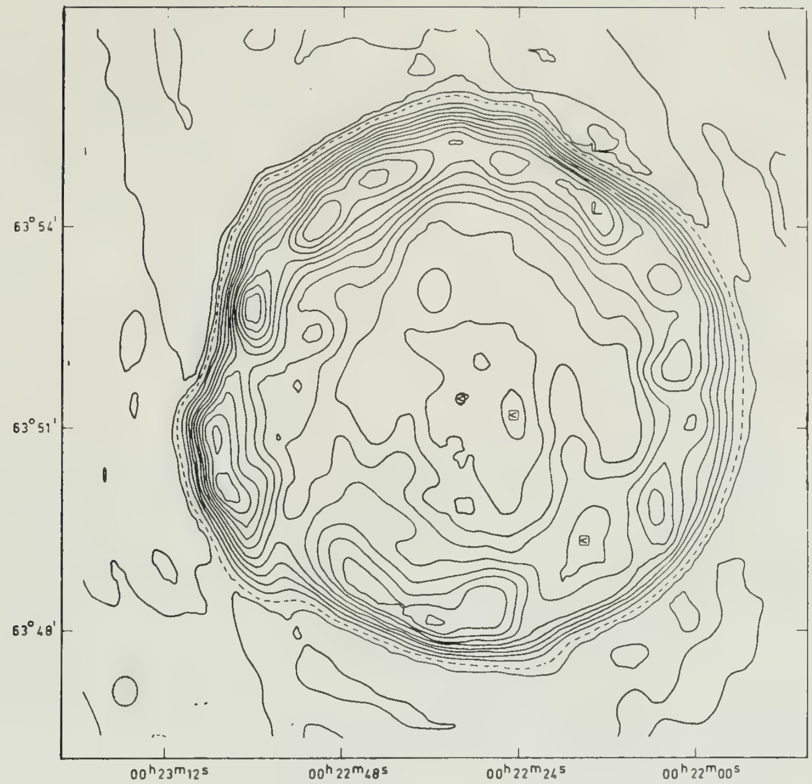

FIGURE 5. *Contour map of the supernova remnant Tycho at the radio wavelength of 21 cm. This emission and some faint optical nebulosities are associated with the supernova detected in 1572 by Tycho Brahe; he determined its (stationary) position and its brightness variation with time. In 1954, the astronomer Walter Baade reconstructed a light curve from these data and found that Tycho's supernova belonged to Type I (after Duin 1974).*

supernova remnants are accessible to detailed observation with radio-telescopes (Figure 5). Here again, the number of observed remnants is consistent with a rate of about one per 50 years for our Galaxy. Most supernovae appear to be restricted to a volume $\sim 9 \times 10^9$ cubic parsecs* (Shklovsky 1961, Clark and Caswell 1976). If we assume that supernovae occur uniformly throughout this volume, then the expected number of supernovae occurring within a distance of R parsecs in t years is

$$N(< R, t) \approx 10^{-12} R^3 t \quad .$$

Thus, in the last 70 million years, we expect one supernova to have occurred within 15 parsecs.

The biologic effects of a nearby supernova can be grouped into two broad categories: (a) effects due to changes in the ionizing radiation environment, and (b) climatic effects (Russell and Tucker 1971). Since the visible light received from a supernova at maximum would be at most a few percent of the light from the Sun, any climatic effects will also be due indirectly to changes in the ionizing radiation environment, which may disturb the radiation balance in the upper atmosphere.

In discussing the extent to which a nearby supernova explosion could change the ionizing radiation environment, I will start with changes we can be sure of and work my way gradually out on a limb as I discuss more speculative possibilities.

The normal cosmic contribution to the ionizing radiation environment consists of cosmic rays which come from the Galaxy and perhaps beyond, and ultraviolet, X and gamma radiation, which comes from the Sun. Table I gives a summary of these contributions.

The characteristic signature of a supernova remnant is the emission of polarized radio waves whose distribution of energy with wavelength is nonthermal, meaning a distribution of a type different from the blackbody

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*One parsec = 3.26 light-years = 3.0857×10^{18} cm.

TABLE I

NORMAL COSMIC RADIATION BACKGROUND

Type of Radiation	Flux at top of Atmosphere
Cosmic Rays	$\sim 3 \times 10^{-3}$ erg cm^{-2} $\sim 10^{5}$ erg cm^{-2} yr^{-1}*
Visible light (3000 - 6000Å)	$\sim 10^{6}$ erg cm^{-2} sec^{-1}
UV (~2000 - 3000Å)	$\sim 10^{5}$ erg cm^{-2} sec^{-1}
XUV (100 - 1000Å)	~1 erg cm^{-2} sec^{-1}
X ray (100 - 0.01Å)	$\sim 10^{-1}$ erg cm^{-2} sec^{-1}

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*Implies a radiation dose rate $\sim 3 \times 10^{-2}$ roentgen yr^{-1}.

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radiation normally associated with a hot object. It is well established that the radio emission from supernova remnants is produced by very high energy electrons trapped in the magnetic field of the remnant. The theory of this radiation, called synchrotron radiation because it was studied in connection with the synchrotron electron accelerators in the 1940's, is well developed, and can be used to obtain reliable estimates of the cosmic ray content of supernova remnants. For remnants having radii between about 1.5 and 15 parsecs, the cosmic ray energy content is about 10^{49}-10^{50} erg (Woltjer 1972). This estimate refers to the cosmic ray energy content of the supernova remnant at any given time; it does not take into account the cosmic rays that have escaped the remnant. For this estimate we must turn to studies of the normal galactic cosmic ray flux at Earth.

If one assumes that the observed galactic cosmic ray flux of $\sim 10^{-2}$ erg cm^{-2} sec^{-1} (Allen 1973) is produced by supernovae occurring at the rate of once every 50 years in the Galaxy, then each supernova must produce $\sim 10^{51}$ erg. Recent gamma-ray observations have shown that the overall galactic gamma-ray flux distribution is in good agreement with the assumption that cosmic rays are produced in this quantity in supernova remnants (Stecker 1975). In addition, there is some preliminary evidence that in the Vela remnant, we may be observing gamma-rays from a cloud containing 5×10^{50} erg of cosmic rays

(Higdon and Lingenfelter 1975). Recent theoretical models of cosmic ray production in supernova remnants also support the conclusion that supernova remnants are immersed in a 10^{50}-10^{51} erg cloud of cosmic rays (Chevalier, Robertson and Scott 1976).

For a supernova occurring at a distance of 15 parsecs, the cosmic ray cloud would arrive over a period of 100 to 1,000 years, during which time the cosmic ray flux would increase by a factor ranging from several hundred to a thousand. This implies a dose rate ranging from 10 to 30 roentgen per year. The lethal dose for most laboratory animals is 200 - 700 r so the animals will not be killed outright, but the dose accumulated over a lifetime could do some harm (Shklovsky 1968, Terry and Tucker 1968). I emphasize that this estimate of a low chronic rate for thousands of years is based on solid observation and theory, which in the uncertain world of astrophysics means that the numbers can be believed to within an order of magnitude.

The effect of an enhanced cosmic ray flux on the ozone layer has been estimated by a number of authors. For an enhancement of several hundred to a thousand the ozone will suffer a depletion ranging from about 30 to 90%; in the latter case the ultraviolet flux reaching the earth is dramatically increased (see Reid paper).

A more speculative possibility is that large quantities ($\sim 3 \times 10^{50}$ erg) of cosmic rays are produced during the supernova explosion. Two models along this line have been proposed. In one, an appreciable fraction of the energy released in a supernova is converted into relativistic particles by means of a strong shock wave which accelerates outward through the star's envelope in a matter of seconds (Colgate and White 1966). In another, large quantities of cosmic rays are produced over a period of months through the agency of intense electromagnetic fields associated with the highly magnetized, rapidly rotating neutron star formed in the explosion (Arons, Kulsrud and Ostriker 1975). In either case, we might expect that a relativistic blast wave would be formed in the interstellar medium and push its way to the Earth over a period of 50 years. The cosmic rays would be concentrated in a thin shell behind the shock front. The thickness of the shell would be of the order of one parsec. The resulting cosmic ray enhancement would be ~10^4; the cosmic ray induced dose rate would be ~300 r yr^{-1} for approximately ten years. This would surely cause problems for life on Earth. As I mentioned earlier, this possibility is more speculative because as yet we have no observational confirmation of the theoretical models. However, in quasars and other violently active extragalactic sources, explosive events in which 10^{50}-10^{52} erg of high energy particles are released on a time scale of months are commonly observed. It is possible that these are just the early phases of supernovae explosions (it has been speculated that supernovae occur in the nuclei of galaxies at the rate of 1-10 per year), but other explanations are also possible.

Finally, X and gamma-ray bursts of 10^{47}-10^{48} erg over a few hours period have been predicted by the theory of supernova explosions and are consistent with the scant observational data (Chevalier 1976, Ulmer, Grace, Hudson and Schwartz 1972). This amounts to a ~10^4 fold increase in the normal X ray intensity. The increase in UV background due to a nearby supernova is negligible. No increase in dose rate is expected from an X ray burst since the X rays are absorbed in the upper atmosphere. However, because of this absorption, the X rays can cause a reduction in the ozone column density which will result in enormously increased UV fluxes from the Sun reaching the Earth, as for an increased cosmic ray flux.

Table II gives a summary of the sequences of events and changes in the ionizing radiation background which could result from a nearby supernova explosion.

TABLE II

PLAUSIBLE SEQUENCE OF EVENTS RESULTING FROM

A SUPERNOVA EXPLOSION 18 PARSECS FROM EARTH

Time since supernova first becomes visible on Earth	
0-10^4 sec (0-3 hours)	X and gamma ray burst, releasing ~3 x 10^{47} erg in hard radiation over 10^4 sec. During this period the X and gamma-ray flux on Earth would be enhanced by a factor 10^4 over the background rates given in Table I. Possibly some effect on ozone layer.
10^5-10^7 sec (1-100 days)	Rise in visible light and UV. At maximum light, the supernova is 30 times brighter than the full moon, but less than a tenth of one percent as bright as the Sun.
10^8-10^9 sec (3-30 years)	Cosmic ray pulse from relativistic shock wave arrives (this is predicted in some but not all models). The cosmic ray background is enhanced by a factor of ~5,000 during this period, implying a radiation dose rate ~200 roentgen yr^{-1} for about 10 yr. Dramatic changes in ozone layer and climate are also possible during this period.
10^{11}-10^{12} sec (3,000-30,000 years)	The expanding shell of the supernova remnant sweeps over the Earth. During this period the cosmic ray flux will be enhanced by a factor ~300, implying radiation doses of ~10 r yr^{-1} for thousands of years. In addition the ozone layer and the climate could be affected.

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ASTRONOMICAL EVIDENCE BEARING ON THE SUPERNOVA HYPOTHESIS FOR THE MASS EXTINCTIONS AT THE END OF THE CRETACEOUS

Paul A. Feldman

1. Introduction

The speculation that a nearby supernova explosion might have drastically affected terrestrial life at the end of the Cretaceous (Haber 1945) has been a topic of active discussion for nearly a decade (Terry and Tucker 1968, Russell and Tucker 1971, Russell 1975, Ruderman 1974, Whitten et al. 1976). It is not my current intention to deal with the specific processes by which a massive dose of ionizing radiation from an assumed nearby supernova (see Tucker paper) arriving at the top of the atmosphere may have led, directly or indirectly, to mass extinctions. Rather, the questions that I wish to consider here are concerned with the specific astronomical evidence that is currently available for or against the occurrence 65 million years ago of a supernova explosion in the neighbourhood of the solar system. In particular, the nature of Lindblad's ring of expanding neutral hydrogen (Lindblad 1967), which has been tentatively suggested in this connection (Hughes and Routledge 1972), is discussed in the context of current pulsar (neutron-star) theory and observation.

2. Galactic Supernovae and Supernova Remnants

The mean rate of occurrence of supernovae in galaxies like our own is approximately one every 30 to 100 years. Quite recently, however, several independent lines of evidence (Tammann in press, Taylor in press) suggest that the supernova rate in our Galaxy may be much higher, possibly one event every decade or two on average. On purely statistical grounds this makes it quite likely that many supernovae occurred within a few hundred parsecs* of the Sun since the Cretaceous. Supporting evidence for this idea is found in the various remnants that supernova explosions leave behind: gaseous debris,

*One parsec (pc) = 3.26 light years

relativistic particles and magnetic fields, and neutron stars (pulsars) (see Figures 3, 4 and 5 in Tucker paper).

A small number of radio-emitting supernova remnants (consisting of relativistic electrons interacting with weak magnetic fields) have been detected within a few hundred parsecs of the Sun (Spoelstra 1972, 1973). However, the characteristic age of these so-called radio "loops" is $\lesssim$several x 10^4 years. In fact, it is probably hopeless to seek optical or radio emission from a normal supernova remnant that dates as far back as the Cretaceous period. After $\lesssim 10^5$ years, the expanding shock front would have been slowed to the local interstellar speed of sound, enabling the shock to become strongly radiative and to cool rapidly. Dissipation and merging of such remnants into the general interstellar gas is expected to have taken place in $\lesssim$several x 10^5 years. Decay of the nonthermal radio emission is expected on a similar (but slightly longer) time scale due to relativistic-particle leakage and synchrotron energy losses, and to magnetic field dissipation, unless the remnant can be re-energized by its pulsar. However, pulsars are expected to be effective in producing relativistic particles for only a few million years at most (Taylor in press).

Sounding rocket surveys of the sky in very soft X rays have revealed large angular-size 'hot spots' of enhanced emission that are probably not more than several hundred parsecs distant (Sanders 1975, Kraushaar 1976). It is possible that these are relatively 'old' supernova remnants, but again they must be <u>much</u> younger than the Cretaceous. To the best of our current understanding, no normal supernova remnant can persist long enough to be older than a few hundred thousand years.

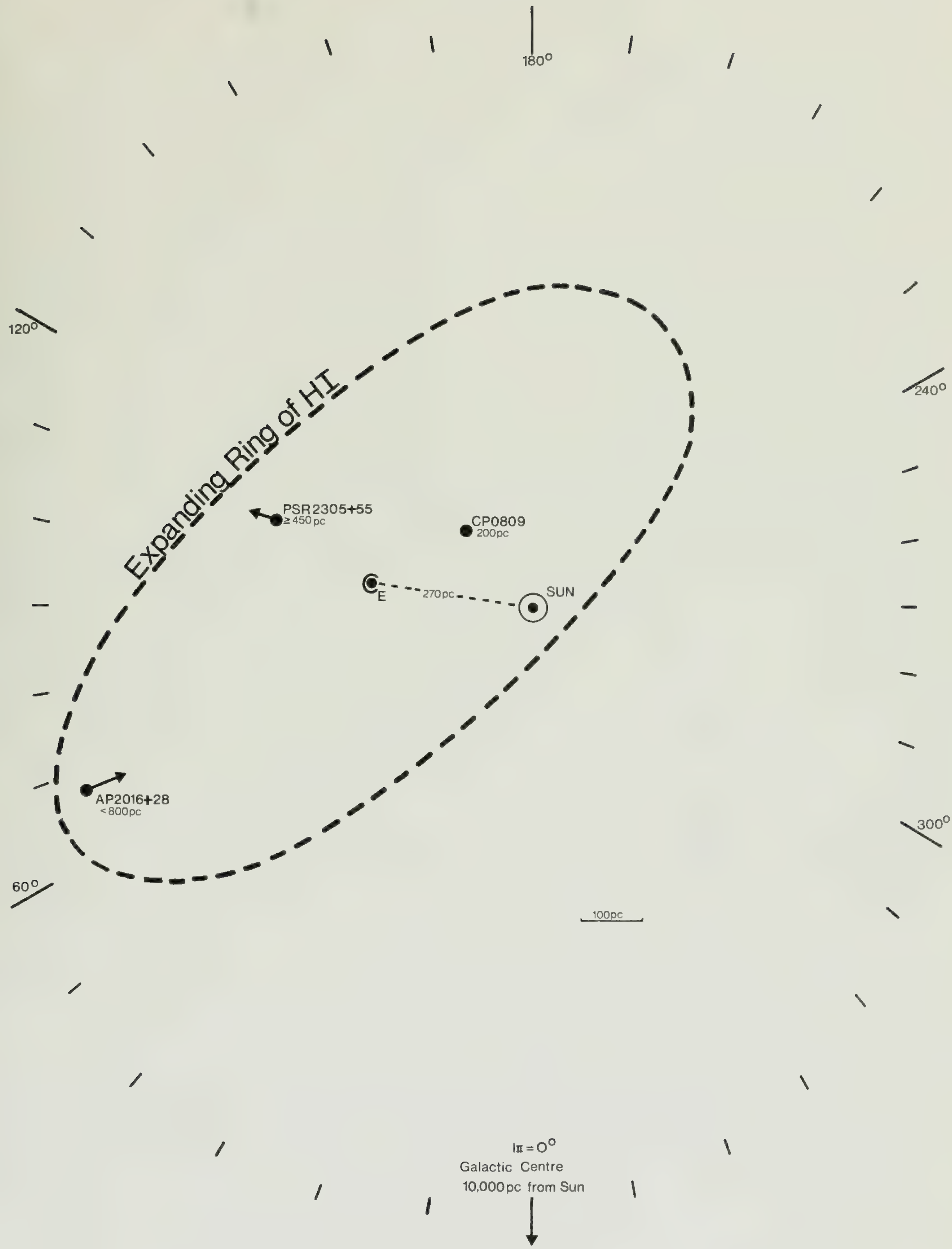
3. Lindblad's Ring

Hughes and Routledge (1972) have called attention to an expanding elliptical 'ring' of interstellar neutral hydrogen (HI) in the neighbourhood of the solar system (Lindblad 1967). While the existence of this particular 'ring' is by no means well-established, similar features do seem to be present in both our own Galaxy and the Magellanic Clouds. Figure 1 schematically illustrates the elliptical ring model consistent with the data. It is centred approximately 270 pc from the Sun* and has major and minor axes of 1300 and 560 pc, respectively. The radial component of the ring's expansion velocity is approximately 6 km s^{-1} (Lindblad 1967), or slightly higher (Hughes and Routledge 1972).

Much attention (e.g. Russell 1975) has been paid to the speculation by Hughes and Routledge (1972) that this possible 'ring' feature might represent the remnant gaseous debris of an extraordinarily energetic supernova explosion (so-called Type III) which occurred in the solar neighbourhood 65 million years ago, coincidently at the time of the mass extinctions. On the face of it this seems rather unlikely. First, there is no observational evidence for the nonthermal radio emission that would serve to confirm the basic supernova (or explosion) hypothesis. Second, astrophysicists have been unable to conceive of any mechanism for stellar explosive death more energetic than the collapse/detonation of a supergiant core and the subsequent expulsion of its outer envelope (Type II supernova). Yet Lindblad's ring seems to require an explosive event at least several orders of magnitude more energetic than is normally expected of such supernovae (see Tucker paper). Third, it is difficult to understand how the ~1 kpc 'ring' of expanding gas could have slowed down to an expansion velocity of only ~10 km s^{-1} without being dissipated and subsequently becoming merged into the general interstellar medium, especially over a time scale of nearly 10^8 years. Fourth, it does not seem possible to deduce from the available data that the ring is precisely 65 million years old, or in accord with the best available dating of the mass extinctions (viz 64 ± 2 million years ago). At least a factor

*The effect of differential galactic rotation on Lindblad's ring since the Cretaceous period is difficult to compute exactly, but it is likely to be negligibly small compared to the uncertainties of the ring model itself. For $\omega_0 = 25$ km s^{-1} kpc^{-1}, Oort constant $A = 15$ km s^{-1} kpc^{-1}, and $R_0 = 10$ kpc, the change in the distance between the Sun and the centre of expansion of Lindblad's ring is only ~12 pc. (This is in disagreement with the estimate of Hughes and Routledge 1972).

FIGURE 1. *Schematic illustration of Lindblad's ring of neutral hydrogen in the galactic plane ($b_{II} = 0°$). Galactic longitude (ℓ_{II}) is given in degrees, on the border of the figure. The position of the Sun, $\odot$, and of the centre of expansion of the ring, C_E, are indicated. The positions of the three pulsar candidates mentioned in the text (see Table I) are shown projected in the galactic plane, but with their estimated distances noted (upper or lower limits to distances are denoted by appropriate arrows). Epoch 1950 coordinates were employed, but the errors introduced by differential galactic rotation are negligibly small in these circumstances.*


180°
120°
240°
Expanding Ring of HI
PSR 2305+55
≥ 450 pc
CP0809
200pc
E
270pc
SUN
AP2016+28
<800pc
300°
60°
100pc
$l_{II} = 0°$
Galactic Centre
10,000pc from Sun

of two uncertainty beclouds any estimate of the age of Lindblad's ring.

4. Relevant Information From Pulsars

Regardless of its apparent implausibility, we shall take the (Type III) supernova hypothesis of Lindblad's ring seriously enough to consider what evidence from pulsar (neutron star) astrophysics can be brought to bear on it.* Pulsars, generally believed to be rapidly rotating, highly magnetized neutron stars, are thought to be left behind following the collapse of the central core of a star which ends its 'normal' stellar life as a supernova. Estimates of both the age and the distance of a neutron star can be made from routine pulsar observations.

We expect that a pulsar's age will be given by a value somewhat less than its so-called 'characteristic' (magnetic-dipole radiation) age $\tau_c = P/2\dot{P}$ (where P is the observed rotation period and $\dot{P}$ is the rate of slow down). General considerations (Ostriker and Gunn 1969) suggest that the age is probably between τ_c and $\tau_c/2$ (pure gravitational-radiation braking), but for most pulsars it is not possible to estimate the true age much better than this. For the Crab Nebula pulsar $\tau_c = 1240$ years, about 1/3 longer than the historically known age of 922 years. Similarly, the characteristic age of the Vela pulsar is 11,000 years, in accord with a recent estimate of 10,000 - 30,000 years for the age of Vela supernova remnant. Some complicating effects that might tend to decrease the estimated age of a pulsar are multipole electromagnetic radiation torques, magnetic-field decay on a time scale of order 10^6 to 10^7 years, and magnetic field alignment with the pulsar rotation axis. Possible effects that tend to work in the opposite direction are the radial deformation of magnetospheric field lines by particle inertia and magnetic field counter-alignment with respect to the rotation axis.

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*After all, a few similar ring-like features do appear to be present in the Galaxy and the Magellanic Clouds. For example, a similarly powerful event seems to have occurred in the Cassiopeia-Perseus spiral arm, at a distance of nearly 3 kpc (Rickard 1968).

The distance of a pulsar can be estimated from the amount of dispersion that the ionized interstellar medium introduces into the observed pulse arrival times as a function of frequency. If it is known that the line of sight to a pulsar passes through an ionized hydrogen (HII) region, a correction is made for its contribution to the total dispersion measure before estimating the distance.

I have examined the most up-to-date compilation of pulsars and their properties which is available to me (Terzian and Davidson 1976) in an attempt to find a neutron-star that might be associated with Lindblad's ring, on the assumption that it might have been formed by a particularly energetic supernova explosion. My selection criteria were: a) that the direction be approximately right, viz $\ell_{II} = 100° \pm 50°$; b) that the estimated distance be reasonably close, i.e. $\lesssim 1$ kpc; and c) that the characteristic age of (magnetic-dipole) spindown, $\tau_c = P/2\dot{P}$, be in the range 60 to 130 million years. Only three pulsars were found to meet all these criteria: CP 0809, AP 2016+28, and PSR 2305+55. Their properties are summarized in Table I.

TABLE I

POSSIBLE PULSAR CANDIDATES FOR ASSOCIATION WITH LINDBLAD'S RING

Pulsar Name	Galactic Longitude (ℓ_{II})	Galactic Latitude (b_{II})	Dispersion Measure ($cm^{-3}pc$)	Estimated Distance (pc)	Characteristic Age, τ_c (x 10^6years)
CP 0809	140°	32°	6	200	125
AP 2016+28	68°	- 4°	14	<800	60
PSR 2305+55	109°	- 4°	45	?>450	110

The (projected) positions of these three ostensible candidates vis-à-vis the location of Lindblad's ring in the galactic plane ($b_{II} = 0°$) is schematically illustrated in Fig. 1.

It is clear that none of the three 'candidate' pulsars is a really good possibility for being the neutron star that might be associated with Lindblad's ring. AP 2016+28 might appear to be the best candidate on the basis of its characteristic age (so close to 65 million years) and its (hopefully) uncertain distance, but this is probably not the case. This pulsar's proper motion has recently been determined (Anderson et al. 1975) by radio pulse arrival-time observations (Manchester et al. 1974); its transverse velocity is found to be anomalously low ($\sim$75 km s^{-1} for the assumed maximum distance of 800 pc) compared to other pulsars (the mean is 200 km s^{-1} for the nine determinations that have been made). The kinematic age of AP 2016+28 that is consistent with its distance from the galactic plane ($\lesssim$55 pc) is probably $\lesssim$1 million years ($\ll \tau_c$ = 60 million years).

The problem of discrepant characteristic and kinematic ages for pulsars is, in fact, a general one (Taylor in press). It is assumed that pulsars originate from a parent population of small galactic scale-height (viz O-B stars). Then, unless pulsars with large characteristic ages ($\gg 10^6$ years) have out-of-the-plane (z-) velocities considerably (and anomalously) smaller than 100 km s^{-1}, they must be much younger than their characteristic ages seem to imply. This discrepancy might be resolved if the large ($\sim 10^{11}$ - 10^{12} gauss) magnetic fields associated with pulsars decayed on a time scale of a few million years (Lyne et al. 1975). However, the viability of this hypothesis remains controversial on basic theoretical grounds (Ewart et al. 1975, Flowers and Ruderman, pers. com. 1976). In any event, the situation is unlikely to be resolved in favour of the characteristic ages being the correct, or more nearly correct, estimates of the true pulsar ages.

As for the other two candidate pulsars, CP 0809 is probably younger than its characteristic age of 125 million years. But it is unlikely to have an out-of-the-plane velocity so low ($\sim$1 km s^{-1}) as to be 65 million years old. A similar argument applies to PSR 2305+55. In fact, if we were to acknowledge the high-velocity nature of pulsars as firmly established, it would be clear that we should seek a 65-million-year-old pulsar at great distances ($\sim$10 kpc) from its birthplace. Thus any pulsar associated with Lindblad's ring would likely now be many kiloparsecs outside the ring's boundaries.

5. Conclusions

Addressing the astronomical evidence for (or against) the occurrence of a supernova explosion in the vicinity of the solar system approximately 65 million years ago:

(1) Recent work suggests that, on a statistical basis, a supernova may well have gone off relatively near the Sun since the Cretaceous period.

(2) The known examples of supernova remnants in the solar neighbourhood are orders of magnitude too young to be considered possible candidates. In fact, no normal supernova remnant can be expected to persist as a detectable entity longer than about 10^5 years; after that it merges into the interstellar medium and becomes indistinguishable.

(3) Lindblad's ring of neutral hydrogen is a very problematic candidate. It is not clear observationally that this ring, even if real, actually represents a supernova remnant. There are no astrophysical bases for either its origin or its subsequent evolution in the interstellar medium. And its quoted age of 65 million years seems more than remarkably fortuitous since the available data preclude such precision.

(4) No currently known pulsar (neutron star) in the general vicinity of Lindblad's ring is likely to be associated with it, begging the questions of its uncertain nature and age. In fact, pulsars appear to be such high-velocity objects that any pulsar dating back to the Cretaceous would now be many kiloparsecs distant from the Sun (and hence well outside Lindblad's ring). It is unlikely that such a pulsar could ever be distinguished, even if we were able to detect it.

(5) Pulsar spindown ages, especially those in excess of several million years, are currently considered very uncertain. The hitherto widely accepted characteristic (magnetic-dipole) spindown age became suspect after proper-motion studies showed that pulsars probably form a high-velocity population with a mean kinematic age of only several million years. It now seems unlikely that pulsars will be able to tell us anything about supernovae older than about 10 million years.

In summary, there is currently no unambiguous and certainly no compelling astronomical evidence that favours the hypothesis that a nearby supernova triggered the mass extinctions at the end of the Cretaceous. Moreover, no such positive evidence now appears likely to emerge from astronomical studies of supernova remnants and pulsars. On the other hand, it is statistically possible that such an event might actually have occurred. We must seek external evidence for its effects, but much 'closer to home': possibly on the Moon and elsewhere in the solar system.

Acknowledgements

I acknowledge helpful discussions with Dr. R. Kirshner on supernova shock evolution, Dr. G. Greenstein on magnetic decay in neutron stars, and Dr. P. Burstein on very soft X ray 'hot spots'. I also wish to thank Dr. R. Roger for bringing Spoelstra's radio "loops" to my attention, and Prof. V.A. Hughes for clarifying some aspects of his paper with Routledge.

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DISCUSSIONS

Individual presentations, questions and informal discussions were recorded during the meetings. An edited version of the discussions was prepared, which is not inclusive and does not necessarily follow a chronological order. All references to one broad subject were grouped under one of five headings: the geosphere, the biosphere, the atmosphere and hydrosphere, the photic sphere, and the cosmosphere. (See p. 153 for notes).

1. THE GEOSPHERE

Norris: Volcanic ash showers resulting from explosive volcanic action (bentonites) are characteristic of the Cretaceous Western Interior sedimentary basin of North America.

Feldman: We might consider extensive volcanism as a cause of the extinctions for at least three reasons. First, major volcanic eruptions can affect the radiation balance of the atmosphere [see discussion of photic sphere]. Second, explosive volcanism might have injected large quantities of hydrochloric acid (and other chlorine-containing gases) into the upper atmosphere. Attack by OH radicals can release atomic chlorine, which can then destroy ozone molecules by the $C\ell$-$C\ell O$ catalytic chain reaction, resulting in a serious depletion of stratospheric ozone. Third, large quantities of fluorides might have been released into the oceans and deposited on land together with volcanic ash. Increased levels of bioaccumulative fluorides are known to have deleterious effects on a variety of organisms,[1] in which fluoride can impair the solubility and/or reactivity of calcium-containing tissues (e.g. skeletal apatite) with consequent reduced availability of calcium for vital physiological processes.[2]

Tucker: Have there been other periods of intensive volcanism in the geological past?

Norris: Yes, but I have not seen as much as during the Cretaceous in North America.

Reid: It is the explosive type of volcanism that is important climatologically, because it injects large amounts of ash and dust into the stratosphere.

Russell:[3] There are two basic difficulties concerning the viability of this model. First, the thermal regime of the Earth is more sensitive now because it is much closer to a threshold of 0°C than it was during the Cretaceous. Secondly, bentonites are found all through Cretaceous and early Tertiary deposits. Why should only the one layer at the boundary have caused major extinctions?

Lemieux: Periods of very intensive submarine volcanic activity may increase oceanic turbidity, reducing the depth of the photic zone and clogging up filter-feeding systems.

Russell: Volcanic ash beds are not characteristically associated with the Cretaceous-Tertiary boundary in oceanic sediments.

Norris: McLaren[4] supposed that a meteorite falling within the Paleozoic "Pacific Ocean" would have generated a wave 20,000 feet high. The induced turbidity would have produced the dramatic extinctions of late Devonian time. Perhaps a meteoritic impact should also be considered in evaluating Cretaceous-Tertiary events.

Roy: Although impacts of major planetisimals were 1000 times more frequent during the first few hundred million years of Earth's and Moon's history than today, the present frequency has remained approximately constant for the last 2×10^9 years.[5] Undoubtedly the collision of a large meteorite (~100 km in diameter) would be spectacular. It is difficult however to understand how irreversible extinctions would be induced if such collisions were so rare.

Russell: Heavy metals occur in an unusual abundance in the fish clay at the boundary in Denmark.[6] Could these have resulted from a meteoritic impact? Would it have affected dinosaurs living in the Gobi of Central Asia, 500 miles from the nearest shore?

Feldman: We might consider the possibility that highly toxic nickel carbonyl was produced by the impact of a large iron or stony iron meteorite, with nickel typically 6-16% of the metallic content.

Béland: If heavy metal poisoning had been widespread enough to explain all simultaneous extinctions, one would expect the fresh-water ecosystems to have been among those hit first, which they were not.

2. THE BIOSPHERE

Lemieux: One of the most puzzling elements in this problem is how the great diversity of living things came to be, toward the end of Cretaceous time. How much is known of, for example, the climatic conditions that made this great diversity possible? If one could understand what caused the diversity one might then be able to better understand why it abruptly fell. Did diverse environmental conditions exist which favoured diversity, or did uniformly favourable conditions without the constraints of many physical limiting factors favour diversity? Did the attainment of a diversity maximum itself trigger a collapse?

Norris: This is a very important question in ecology. One point of view holds that climatic oscillations act like species pumps. During an oscillation species become extinct and new species evolve to restore former diversity levels. Another holds that environmental stability is essential to creating high diversity levels.

Russell: Whatever the climatic or environmental conditions were that produced this great diversity at the end of the Cretaceous, within 20 million years former diversity levels had been nearly re-attained, although the adaptive "finesse" of Cretaceous organisms had not been completely restored. This would imply that Cretaceous environmental conditions were not interrupted for a great length of time.

Béland: It would seem that the reptiles filled a large spectrum of niches on land, and about 20 million years were required after the great biotic perturbation for mammals and birds to radiate into a comparable spectrum of niches.

Jarzen: In angiosperms, Cretaceous diversity and adaptive finesse had been surpassed after 20 million years.

Pirozynski: Looking at the taxonomic diversity figures [see Russell paper] I wonder if we are comparing categories of equivalent taxonomic weight.

Russell: This would seem to be generally so, although there are other limitations in that the terrestrial record is here confined to the interior of our continent, and the marine record is largely based on sediments bordering the northern part of one oceanic basin. The sample is anything but complete; we hope it is representative, and it does suggest a problem of great theoretical interest.

Jarzen: Of the figures given, those relating to fresh-water environments are based on only a few works as opposed to the scores of papers which have appeared on the marine planktonic record. However, we have to work with the information we have.

Russell: Is there a change in fungal diversity across the Cretaceous-Tertiary boundary?

Pirozynski: The sac fungi, or ascomycetes, seem to appear during Cretaceous time. The morphology of their spores was less well defined or stabilized then than those of modern sac fungi. The spores were generally thin-walled, not very highly melanized and do not occur in abundance in sedimentary rocks. Pollen outnumbers spores in a ratio of perhaps 100 to 1. In more modern samples, dating from about 50 million years ago the proportions can be reversed and fungal spores may outnumber other palynomorphs by 100 to 1. A great explosion in fungal diversity occurred at the beginning of Tertiary time, and it may be that modern thin-walled spore types were a subsequent, secondary development.

3. THE ATMOSPHERE AND HYDROSPHERE

Russell: What would occur [see discussion of photic sphere] if lights were shut off for one year? Seasonal temperature variations in the North Atlantic would suggest that oceans could cool appreciably during this time.

Reid: Dimming the light for an extended period would have profound climatic effects.[7]

Foster: Would temperatures be warmer or colder?

Reid: I suspect it would be colder.

Béland: If the climate became colder, small bodies of fresh-water, which are less buffered than oceans, would be more affected. But this does not seem to have been the case.

Tucker: Could the oceans have become warmer, without fresh-water bodies being affected?

Reid: In photographs of sediments at the boundary [see Russell paper] there is a colour change around the boundary. What is the meaning of it?

Russell: I don't know. There is always a colour change and an increase in the energy of sedimentation. Does it indicate a climatic change?

Norris: Colour changes are commonly seen throughout the sedimentary column, but they are not necessarily associated with any special events.

Russell: In the Alabama section, it was noted that terrestrial plant debris occurs in more than usual abundance at the Cretaceous-Tertiary boundary, and a short-term regression was suggested as possibly having caused this [see Norris paper]. How would one distinguish between a brief regression and increased storminess in this instance?

Norris: It could not be done from a palynological point of view. On the other hand, sedimentological studies could readily distinguish between the two agents, and storm deposits have been documented in similar sediments elsewhere.

Reid: What puzzles me is that one can point to a single thin layer in the sediments, below which the rocks are deposited one way while those above are deposited another way. Can an event like a supernova change irreversibly what will happen for millions and millions of years to come?

Feldman: It seems to point to a climatic change. A supernova can do three things: produce a strong radiation dose at the top of the atmosphere, deplete the ozone layer to allow significantly more UV radiation through, and also affect the climate through its action on the atmosphere.

Béland: The extinctions do not imply strictly different and exclusive causes.

Russell: David Jarzen has noted that the palynological record suggests terrestrial plants were resistent to the causes of the extinctions. Is it possible that the vegetation on mountains and other elevated areas was eliminated and that these newly eroding areas would account for the large amounts of sediments which accumulated in the basins where our data was gathered?

Tucker: What is the most favoured explanation for the extinctions?

Russell: I think the most favoured explanation is the one revolving around mid-oceanic rifting. When there is high activity, the ridges project into the ocean basins and the sea transgresses. When the activity is low, ridges subside and the sea regresses. Such a regression is postulated to have occurred at the end of the Cretaceous. The exposure of the continental shelves eliminated shallow-water organisms and caused a major imbalance in the biosphere. Briefly, flaws in this theory are that the withdrawal was not a worldwide phenomenon and that inland ecosystems would not be drastically affected. Others, such as Tappan, have suggested that a transgression occurred in late Cretaceous time. The reduced land area cut down the supply of nutrients to the oceans, causing phytoplankton populations to crash and the production of oxygen to be drastically reduced. A flaw here is that mountain ranges were present in late Cretaceous times, and I do not feel that nutrients would have been rare everywhere under these conditions.

Reid: The sedimentary records seems to suggest that rivers continued to flow at least with some vigor during this time so that some nutrients should have reached the oceans.

Norris: The record shows that a group of calcareous nannoplankton, originating in Jurassic times, reached their acme in late Cretaceous, depositing enormous quantities of calcareous sediments. These chalks were deposited as calcite crystals whereas prior to this most fine-grained limestones were deposited as aragonite crystals. After the boundary event, these chalk oozes did not accumulate to the same extent. Some people have postulated that these extinctions were caused by a dramatic rise in the carbonate compensation depth (CCD), the depth at which carbonate is dissolved, during the late Cretaceous. The CCD depends on the calcium carbonate budget of the oceans. The carbonates deposited on the shelves, above the CCD, are recycled back. If the CCD rises above the level of the shelves, carbonates are dissolved. This was a major event in geological history. The marine phytoplankton is an oxygen pump and its temporary removal might have had a deleterious effect on the oxygen reservoir.

Russell: How long would the atmosphere remain breathable after a cessation of oxygen production by phytoplankton?

Norris: It is uncertain whether phytoplankton is as important as or more so than land plants in producing oxygen for the biosphere. Some consider it to be more important.

Reid: It has been speculated that if all plant and animal life suddenly died, only about 1% of the atmospheric oxygen would be used to oxidize these tissues. It would require millions of years for the remaining 99% to be captured in the sedimentary-organic cycle. There is a colossal reservoir of oxygen in the atmosphere.

Norris: Is the continued respiration of lung and gill breathers considered in models of oxygen depletion?

Reid: I am not certain, but in either case there could only be a small decline in the oxygen content of the atmosphere. Is there any evidence that atmospheric oxygen levels were higher during Cretaceous times when these nannoplanktonic forms were so abundant and presumably active?

Norris: These forms are still present or others have filled their ecologic space. Replacements are common among planktonic algae and probably the total biomass and productivity of phytoplankton were comparable to present-day levels. And the production of oxygen would have been the same. But there could have been a gap in between.

Foster: Can it be determined whether the sudden disappearance of some shells in sediments is due to a rise in the CCD or to the actual extinction of those forms?

Russell: In Denmark, there is continued carbonate deposition across the boundary, but a drastic reduction in the number of species.

Foster: Why would the CCD suddenly rise in a short period of time?

Russell: Does the rise of the CCD kill the organisms themselves, or is the rise a result of their death from some other causes?

Norris: Any micro-organism with a calcium-based skeleton could not survive long below the CCD. It is also possible that an imbalance in the calcium carbonate budgets could have been triggered by a drastic change in the CO_2 content of the atmosphere.

Feldman: Assuming that the partial pressure of oxygen did become higher, would it have changed the atmospheric equilibrium and affected the ozone layer?

Reid: The ozone layer would move higher, up to the same effective oxygen depth.

Feldman: Then the ozone layer would become more susceptible to destruction by radiation from extraterrestrial sources.

Russell: It seems possible that the sediments after the extinctions were more heavily oxidized. This question, together with the observed colour changes, deserves investigation.

Lemieux: What would happen if the temperature gradient on the warm Cretaceous Earth were changed by decreasing mean temperatures at the poles by 5°C?

Norris: The record does suggest that the poles were warmer then with mean oceanic temperatures of about 12°C as opposed to tropical surface water temperature of about 23°C.[8]

Reid: There must have been something vastly different in the radiation balance to produce a gradient like that. Continental drift might do it on a long term scale, by altering oceanic and atmospheric circulation patterns. Perhaps if the Earth's axis of rotation were vertical the same effect could be achieved.

Pirozynski: How would a change in the pH of oceanic waters affect the organisms?

Norris: Even slightly acidic waters would dissolve carbonate shells.

Russell: But would sea-water be too well buffered for a sharp change to occur?[9]
Is there a possibility for cosmogenic production of poison through high-energy bombardment of the atmosphere?

Reid: I doubt it.

4. THE PHOTIC SPHERE

Foster: Could a significant drop in available light constitute a biological stress that would account for most of the extinctions?

Norris: In the Mesozoic, dinoflagellates have been found in high latitudes associated with mineral pseudomorphs which form only in seasonally freezing seas such as the White Sea. This indicates that northern seas froze over then during the winter, although there were no ice caps. In seas that are frozen or dark for part of the year, phytoplankton production is limited to a short period. A temporary shut-off of the light might pass without effect. This is in contrast with tropical waters where production is tuned to constant light and temperature conditions. A shut-off of light might have catastrophic effects.

Foster: Can a drop in light affect most marine life but not affect fresh-water ecosystems?

Béland: Oceanic waters have a food chain based on phytoplankton produced in the photic zone. If production there collapses, the whole system follows. On the other hand, small fresh-water streams have a food chain based on nutrients, dead leaves and plant material, insect larvae, decaying matter, etc... produced in terrestrial ecosystems and carried or washed down into the streams. They would perhaps not be affected by a world-wide collapse of phytoplankton production per se. Actually, even after terrestrial plant production ceased, they could survive on continued run-off. The situation would be different for large bodies of fresh-water where phytoplankton is important. Is the fossil evidence relating to Cretaceous fresh-water environments mostly from stream or lake deposits?

Russell: Our knowledge is preponderately based on sediments associated with stream systems, although lake deposits of this age are known from Alberta and Saskatchewan (Battle Formation) and from the Gobi of central Asia.

Béland: Is there evidence that these systems collapsed?

Russell: No, the paleobiology of these ancient lakes is essentially unstudied.

Jarzen: Land plants as a group are adapted to a wide range of light conditions. There are plants thriving in the much-reduced illumination of a rain forest and others living in bright deserts. Where light drops by around 50% or perhaps even more in cloud forests, plants may become dwarfed and scraggy, although diversity may remain at relatively high levels. Some trees attain a large size with almost no sunlight. The palynological record in this case would not discriminate between normal and reduced illumination. What percentage of reduction in light is needed for the pollen record to be affected? And would even a total but geologically short absence of light be recorded?

Foster: Is it possible then to dim lights enough to kill oceanic phytoplankton but not land plants?

Russell: If land plants had not been significantly affected, dinosaurs would have survived. The herbivores would have continued to feed in the twilight as well as at midday. There would have been no food-related reason for their extinctions if their food supply had remained unchanged.

Reid: I cannot see Mongolian dinosaurs, 500 miles away from the sea, affected by a crash in phytoplankton.

Feldman: Consider the lights being dimmed even more, for a period of time long enough to kill land plants as well. This would not necessarily pose a serious problem to the paleobotanists. Would the plants not eventually regenerate from seeds?

Jarzen: ... Plants also regenerate from rhizomes and root systems.

Reid: Would a one-year drop in light be enough to kill all dinosaurs?

Russell: The paleontological record shows that small land vertebrates survived, as well as soft-shelled turtles and crocodiles. These animals can survive in hibernation for several months if the climate is not too cold.[10] Small mammals survived too, and probably could have sustained themselves on nuts, seeds, insects, bark, etc. for several months.

Foster: By what mechanisms can light available to the biosphere be significantly reduced through the effects of volcanism or a supernova?

Reid: Speculatively, a supernova could cut down the light by increasing the amount of NO_2 in the atmosphere. Nitrogen dioxide is selective in the light that it absorbs and has a very high absorption cross-section in the blue. Blue light does not get through at all. At wavelengths longer than about 4000 Å the picture is less clear, in that NO_2 does not dissociate when it picks up light. Some of the light may be simply reradiated, so that light levels above 4000 Å would not be reduced as much. Higher in the spectrum absorption becomes weaker, so that red light is affected very little. This is why city smog has a brownish colour.

Béland: Since red light does not penetrate water as well as blue light, the photic zone would become very thin. Phytoplankton production would be drastically reduced.

Jarzen: Land plants seem to do well in red light.

Foster: Turning off the lights for a year or so means that plants and herbivores would die. When the lights are turned on again, the plants would regenerate vegetatively and from seeds.

Reid: But there would be no herbivores to eat them. After the lights are turned off, any survivors would be those capable of living in low light conditions. When the lights come back, they would emerge from the shade. Would not small lizards be more likely to survive than large tyrannosaurs?

Béland: All forms living on dead or decaying matter could survive for awhile, such as many insects, for example.

Russell: Scavengers feeding on dinosaur carcasses could not. Land forms that reproduce through resistent eggs, such as some snails, would be able to bridge the period of darkness. Even the viviparid snails are very conspicuous by their survival through the boundary.

Feldman: It could be enlightening to know what peculiarities in metabolism, life cycles or niches might be common to all the surviving taxa.

Russell: This might not lead anywhere since there would be food chain phenomena: higher links disappear when their support is removed for some other reason.

Béland: Why not start by removing the top of the pyramid instead of the base. For example if herbivores are controlling plant growth, would their removal not make the whole machine unbalanced?

Tucker: Then we do not know enough of this pyramid, or even if it is a good pyramid. It could have been a column.

Russell: Going over the list of extinctions, I do not see a common pattern among terrestrial organisms. All major groups of reptiles were affected, but especially those containing large forms. All mammals were small and many survived. In the marine world, how is it that the coccoliths did not survive a darkness while the dinoflagellates did?

Norris: Dinoflagellates could coast across a period of darkness by encysting and dropping to the bottom to return later. Some cysts have been revived after almost 15 years burial in sediments. It is also worth pointing out that the majority of them have organic walls, not calcareous skeletons. And in the little work we have done in the Alabama section, I am impressed by the fact that there is no wipe-out of dinoflagellates whereas other groups have shown extinctions.

Russell: Diatoms also go through despite a lack of light. Radiolarians and foraminifers graze on phytoplankton, therefore we expect them to undergo extinctions too, although radiolarians do not.

Béland: ...Here is proof that radiolarians fed on dinoflagellates and diatoms while foraminifers fed on coccoliths!

Russell: All other events in the marine world can perhaps be explained through a collapse of the food chain.

Foster: What mechanisms other than production of NO_2 would cut off blue light?

Tucker: Besides this mechanism, there could be the passage of the supernova shell through the solar system, like a cloud passing in front of the Sun. It might take a year or two years for the dense part of the shell to pass.

Russell: What would be the time lag between the actual explosion and the drifting of the shell past the Earth?

Tucker: It is difficult to be certain. The present-day theory holds that a shell would dissipate in about one million years. However, the particular shell we discussed earlier [see Feldman paper] is apparently 60 million years old. Perhaps it is possible that a shell from a supernova which happened a long time ago and far away could still be dense enough to dim the Sun as it coasted by, or could push an interstellar cloud our way with the same result. Hughes and Routledge [see Feldman paper] were looking for comparable systems of moving clouds and this is an avenue of research which could be investigated more thoroughly.

Reid: As these filamentous structures swept between the Earth and the Sun, they might have produced a cooling. Some have thought that such events could even produce the beginning of an ice age.[11]

Feldman: Blue light could also be cut off through an effective cooling of the solar radiation, e.g. by means of a giant sunspot group or by the passage of the solar system through a relatively dense cloud of interstellar dust and gas.

Roy: A small change in the solar spectrum implies a tremendous change in luminosity.

Feldman: My meaning is that the blue end of the optical solar spectrum might be significantly diminished by the presence on the Sun of an enormous magnetic region, with dimensions of several 100,000 km. Even from what little we know about the Sun this possibility seems unlikely, but there are late G-, early K-type stars known in the solar neighbourhood ($\leq$100 pc) with periodic optical variations which have been attributed to regions of "starspots" covering significant fractions of their surfaces.[12]

Tucker: There is another side to the coin. If giant sunspots occur, they would be linked with high levels of solar activity. I am assuming that the solar core keeps generating the same amount of energy, which is carried off by radiation and convection. There would be more flares and more high-energy radiation.

Roy: Very large sunspots covering for example 5% of the solar surface, would diminish the solar luminosity by less than 3-4%. Therefore it is unlikely that blue light would diminish significantly on Earth. Gigantic spots with large magnetic fluxes would likely be accompanied by intense flare activity which would release enormous amounts of high-energy radiation and cosmic rays. The radiative output of the Sun would remain roughly constant but its spectral redistribution would lead to a 'hardening' of the solar radiation, with greater effects on the terrestrial atmosphere. The activity related to such spots would therefore undoubtedly lead to a dramatic enhancement of UV radiation and X rays. Would an increase in UV account for the apparent abundance of melanized spores in strata of basal Tertiary age?

Pirozynski: A sudden environmental perturbation could simply eliminate those forms not protected by melanin, and the survivors would all be characterized by high melanin concentrations. However, it must be kept in mind that chemical methods used in palynomorph extraction may also destroy the thin-walled spores.

Norris: Interestingly, heavily melanized fungal spores may be very common at some localities in high latitudes in sediments deposited about 55 million years ago. Often few other palynofossils are present. Fungal spores are however frequently quite diverse, and because they are heavily melanized they may be extracted from the sediments using standard chemical techniques.

Béland: David Jarzen has noted that in general animals cannot withstand unfavourable environmental conditions as well as plants, and take advantage of their mobility to seek out more favourable micro-environments. Could fungi survive as well as plants do by means of root sprouts and long-dormant seeds?

Pirozynski: Fungal spores and spore-bearing bodies can remain viable for years. In one experiment specimens were freeze-dried and sealed in glass tubes at the beginning of the century. Every decade one tube has been opened and the specimens tested for viability. After 50 years, there had been no loss of ability to shed viable spores.[13]

5. THE COSMOSPHERE

Roy: I would like to note that it is not possible to demonstrate that giant solar flares did, in fact wipe out the dinosaurs. However, limitations in astrophysical knowledge as far as estimates of solar output are concerned can be defined. The geological changes across the Cretaceous-Tertiary boundary are striking and whatever happened at the boundary was dramatic enough to be imprinted in the rocks themselves, as remarked by George Reid. I would, however, dare to suggest that unusual solar activity could have dramatically amplified environmental stresses at a time of more than usual biological instability, precipitating the extinction of species already in decline.

Is it possible to scale the expansion of a supernova remnant, so that the size it will attain in 60 million years can be estimated?

Tucker: The ring initially expands at a velocity of the order of thousands of kilometers per second. Gradually, it cools and slows. Normally, supernova remnants are thought to dissipate within a million years, rather than 60 million years, when they reach maximum diameters of 30-60 parsecs rather than 200-250 parsecs.

Feldman: The properties of really large, so-called type III supernovae are very poorly understood. Even their existence is a matter of controversy. Some have postulated that they liberate 10^{51} to

10^{53} ergs and that they occur in the neighbourhood (several kiloparsecs) of the Sun with a frequency of once in 10^7 years.[14]

Tucker: Yet the gigantic ring described by Lindblad, as well as comparable structures in the Magellanic clouds almost forces one to conclude that these gigantic explosions exist, although they have not been mentioned in terms of theory. Have the proper motion of any of the pulsars within Lindblad's ring been measured?

Feldman: Hughes and Routledge point out that there is some evidence for very powerful explosions in the Cassiopeia-Perseus arm of the Galaxy at a distance of 2.9 kiloparsecs from the Sun, and elsewhere.[14] The evidence suggests energies of expansion several orders of magnitude greater than is likely for a type II supernova. This is really fuzzy territory, however. Perhaps we would be in a better position to understand what sort of cataclysmic event might lead to a type III supernova if we knew something about its UV, X ray and cosmic ray production. If we take the existence of Lindblad's ring seriously, it might be worthwhile to consider how such an event could have affected the solar system. The Moon is a laboratory for studying cosmic ray events of millions of years ago. Peter MacKinnon recently pointed out to me that one lunar rock sample (number 14301), a breccia, is known to possess a large cosmic-ray fission-track excess dated at 102 ± 30 million years B.P. This is perhaps noteworthy in this context. The fission-track excess has a high solar component, making it far more likely to be of solar rather than supernova origin. Nevertheless, lunar-rock experts, particularly those who study fission-tracks, should be made aware of cross-disciplinary interest in their work.

Reid: Unfortunately the soil of the Moon is continuously disturbed by meteoritic impacts.

Douglas Russell: Our chemistry group specializes in trace analyses which are carried out through a number of instrumental techniques encompassing emission spectroscopy, mass spectroscopy and atomic absorption. We are interested in parts per million components in a number of materials including rocks, soils, water and, more recently, base metal concentrations in sea water which are 10 to 100 times lower than in fresh water, or in the range of parts per billion. Two special techniques being used here are plasma excitation, and photon activation. At some time in the future it might be possible to include in our programme analyses of materials of interest to this group.

Foster: I believe analagous studies have been carried out in sedimentary rocks. What was the theoretical basis of the studies, and how might it apply to the situation under consideration here?

Russell: We know that certain isotopes are created in the atmosphere through the bombardment of the Earth by high-energy radiation. We know that "fossil" isotopes can be preserved in the sedimentary record.[15] Is it possible or feasible to detect in sediments that were being deposited at the time of the extinctions cosmogenic elements or fossil isotopes which might provide clues to the cause of the extinction? Or, conversely, might a significant absence of a cosmogenic element or isotope invalidate the supernova or solar flare model?

Reid: The chances of finding a record of such an event would be much greater on the Moon, or on some solid surface beyond the atmosphere. Carbon 14 is created in our atmosphere but it decays. Iodine 129 has been detected in meteorite fragments and has a half-life of 17 million years. It decays into xenon 129 which is easily separable from other stable xenon isotopes. There has been recent consideration of xenon in meteorites in connection with the origin of the solar system.[16]

Foster: What would one expect to find in the sedimentary record as a consequence of a nearby supernova or a solar flare?

Russell: Concentrations of beryllium 10 and aluminum 26 in certain marine strata have been correlated with pulsars, or supernova remnants, back to about three million years ago.[17]

Feldman: It might be useful to look for iron nuclei, which are emitted in solar flares.

Roy: There are evidences that heavier ions are preferentially accelerated during solar flares. At energies lower than 15 MeV per nucleon, the particle flux from solar flares is enriched in heavy elements by an amount that increases with charge number and decreases with energy. This enhancement is suspected to increase up to elements with charge $Z \approx 54$.

Douglas Russell: Boron 9 or 10 have large cross-sections, and concentrations of these could be determined in sediments.

Tucker: It would perhaps also be useful to consider nickel concentrations with respect to nearby supernovae. It might be better to search for the isotopes on the Earth than on the Moon, for here they would be buried and protected from continuous exposure to the Sun over great periods of time.

Foster: If the target product enters the ocean, and settles out on the ocean floor, it would be well shielded both by water and sediments. What, then, could one search for in marine sediments?

Reid: Xenon 129 would be good, or Iodine 129.

Roy: The gravitational time scale for the Sun as a whole is 30 million years. This is the characteristic time over which the solar luminosity would change if supplied by gravitational contraction only. There exist other possible time scales related to intermittent mixing of the solar core or to changes in efficiency of the convective transport of energy through the solar envelope; these time scales range from 2 million to 20,000 years. Such fluctuations may in turn modulate the solar magnetic cycle. Is there any evidence on Earth for 30 million-year or shorter period climatic variations?

Norris: We are near a thermal low now, there was another about 30 million years ago, and a third in the vicinity of the Cretaceous-Tertiary boundary [see Norris paper].

Roy: The same periodicity should be evident in the geologic history of Mars, and it will be interesting to see if climatic fluctuations there are synchronous with those on Earth.

Feldman: If the Earth experiences a cooling every 30 million years, how was it that a particularly susceptible group of organisms existed 65 million years ago, but not 30 million years ago, or now?

Norris: A particularly delicate physical situation may have existed 60 million years ago, with groups of organisms of average susceptibility. A phytoplankton collapse could have been triggered by a widespread transgression and consequent depletion of oceanic nutrients, or by a temperature decline [see Norris paper]. Unfortunately, the evidence could be better, for the relative abundance of phytoplankton during this time interval is based on phytoplankton diversity rather than population estimates. Nevertheless, it should be kept in mind that physical parameters may have been more sensitive at this time than biological ones.

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CHAINS OF EVENTS LEADING TO MASS EXTINCTIONS: TWO SYNOPSES

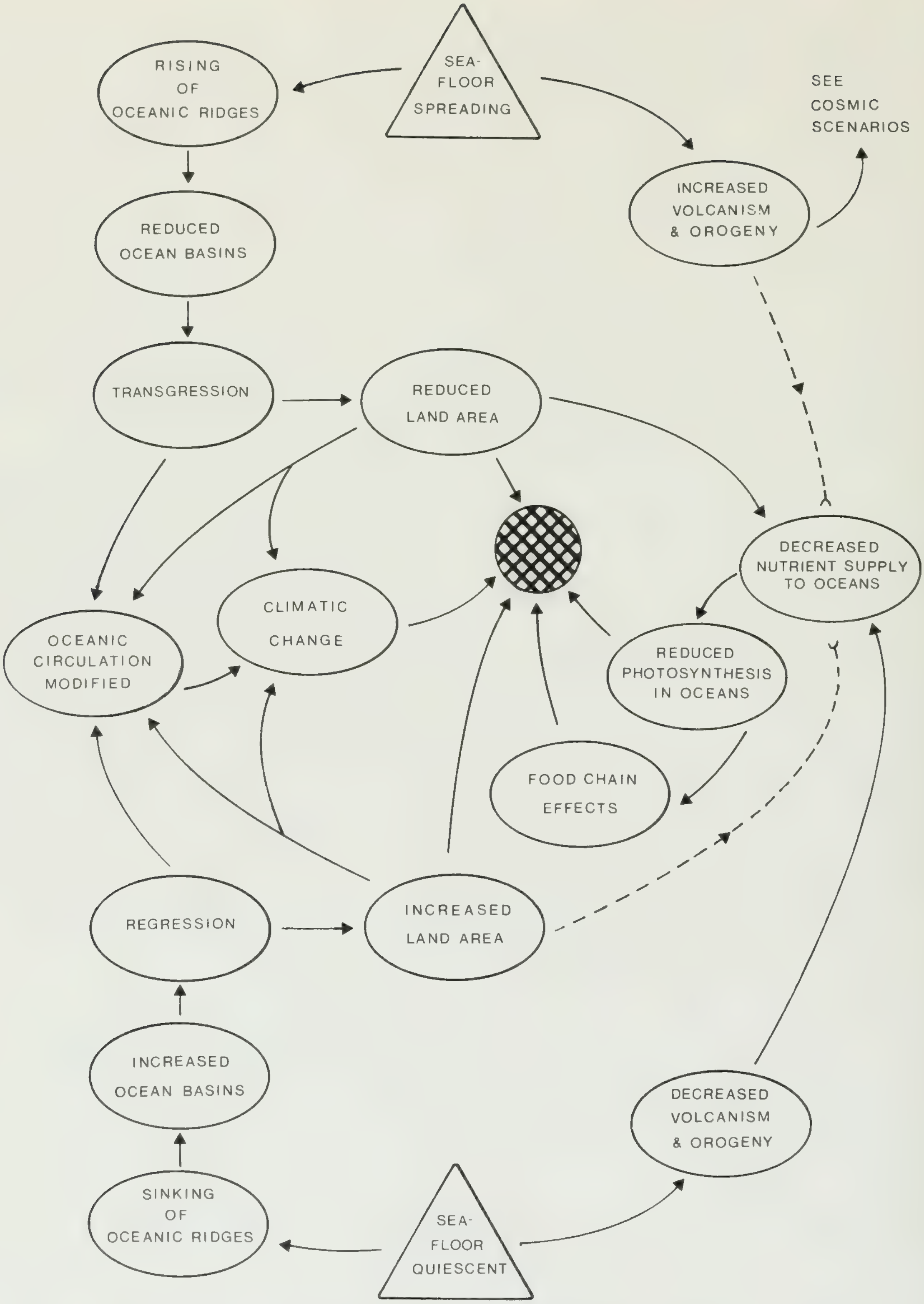
Pierre Béland, Jean-René Roy and Dale Russell

Extinction events are a common and inevitable consequence of an evolving biosphere. Many subtle mechanisms may be involved in the isolated extinction of a single species, but are often extremely difficult to detect in the fossil record. However, in the case of extinctions as widespread and profound as those which apparently coincided with the Cretaceous-Tertiary transition, it is difficult to believe that a substantial body of information could not be extracted from the sedimentary record. Evidence already available from this record was discussed in the course of the workshop with respect to several hypothetical models. We herein attempt to combine most of them into major "scenarios," or chains of causes and effects leading to major extinctions within the biosphere (see diagrams). The first diagram considers terrestrially-limited environmental stresses; the second incorporates stresses of extraterrestrial origin.

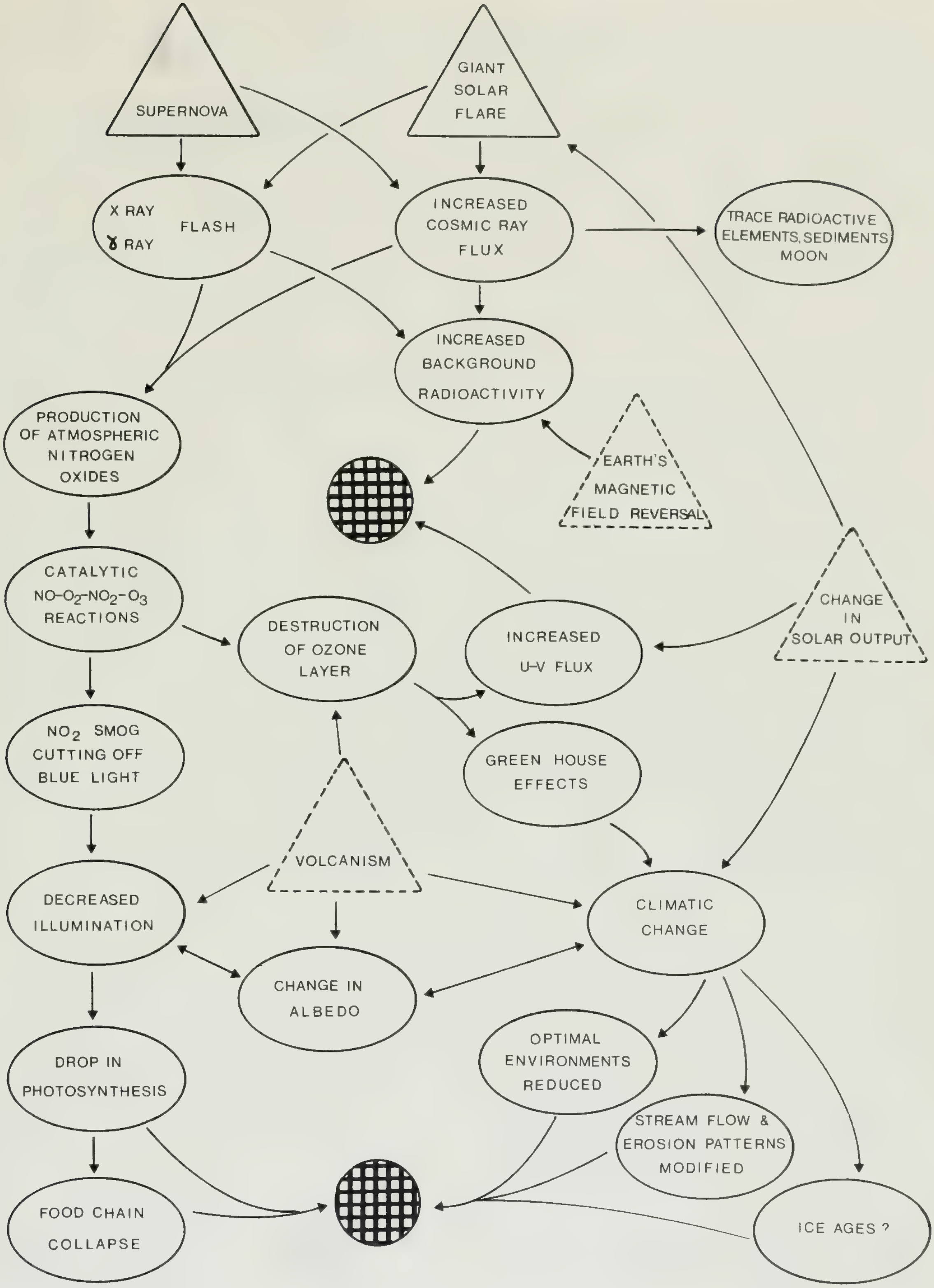
The terrestrial scenarios schematically summarize explanations revolving around marine transgressions and regressions, which are in turn produced by variations in the rate of sea-floor spreading. Extinctions result from four major stresses:

- terrestrial habitats are diminished as seas transgress over low-lying land areas; alternately, marine habitats are reduced when continental shelves are exposed following regressions;
- as seas transgress, nutrients from the land dwindle, phytoplankton productivity declines and marine food chains are disturbed. However, the increased orogeny and volcanism associated with transgressions have an antagonistic effect on the nutrient supply;
- global climatic changes result from major redistributions of seaways and land masses;
- atmospheric dynamics are altered by periods of intense volcanism associated with rapid sea floor spreading.

The cosmic scenarios illustrate a sequence of events postulated to occur as a consequence of a giant solar flare or nearby supernova, both of which



Terrestrial Scenarios



Cosmic Scenarios

produce similar effects in the Earth's atmosphere. Major biotic stresses result from:

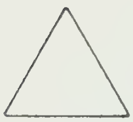
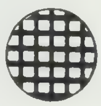
- reflection or absorption of light essential to photosynthetic activity;
- climtic changes resulting from alterations in the thermal structure of the atmosphere;
- increased high-energy radiation within the biosphere.

Other independent agents of biotic stress are also included which might, if occurring coincidentally, enhance the deleterious effects of the primary agents:

- a disappearance or weakening of the Earth's magnetosphere during a polarity reversal;
- a change in solar radiation;
- increased volcanism.

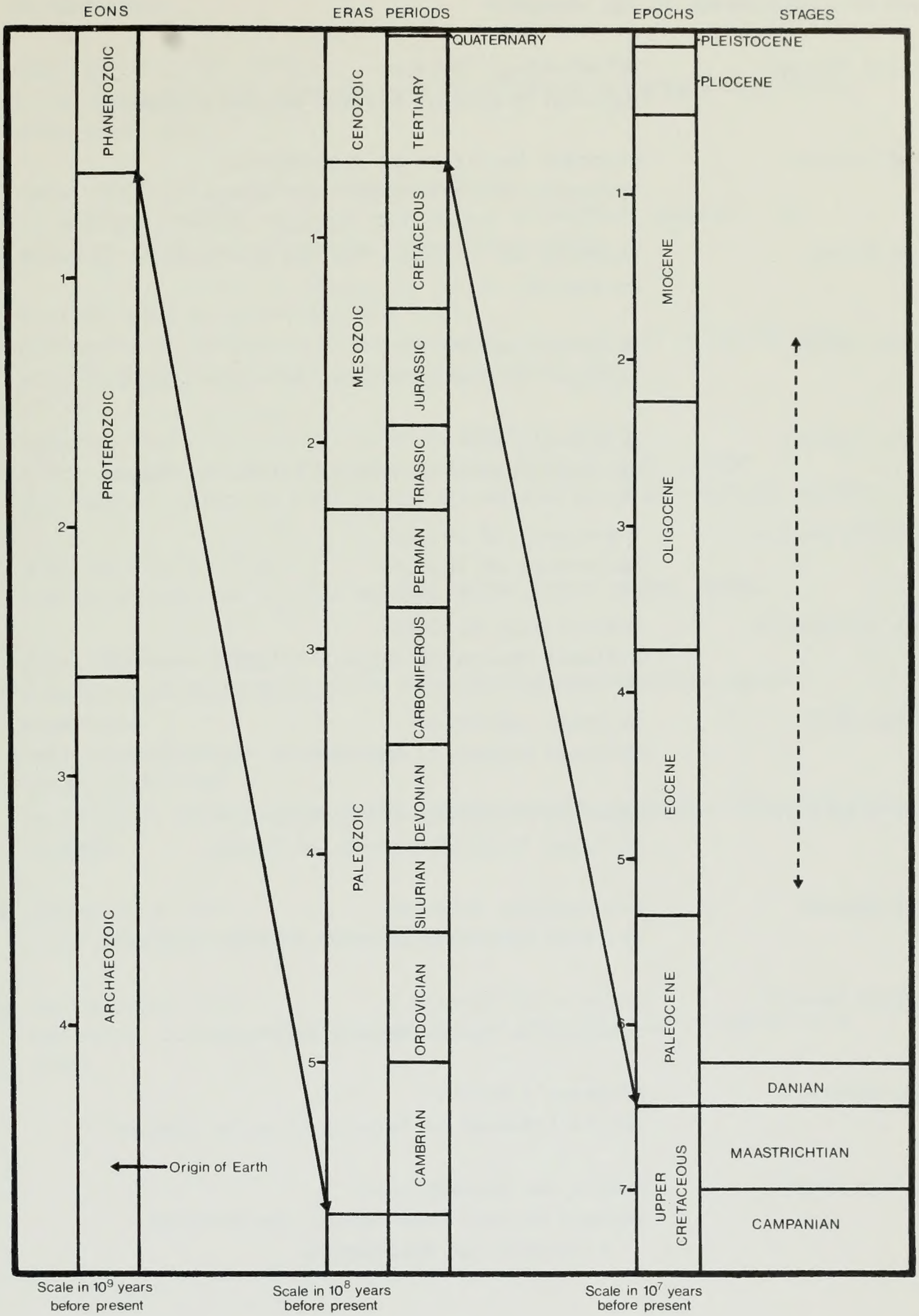
We have neither adequately summarized the workshop, nor do we feel confident of the direction of all of the processes illustrated. Certainly, additional links could be illustrated and other stress agents considered (meteoritic impact for example). However, these scenarios are outlined in the hope that interested readers will amend the weaker aspects and further explore those areas which appear to be promising in the investigation of the Cretaceous-Tertiary environmental changes.

The following symbols are used in the diagrams:

	primary cause		positive effect
	reinforcement from independent phenomenon		counter effect
	event		biotic extinctions.

GEOLOGICAL TIME SCALE

Compiled after Berggren, W.A. and J.A. Van Couvering 1974 (Palaeogeogr. Palaeoclimatol. Palaeoecol. 16:1-216), Van Hinte, J.E. 1976 (Am. Assoc. Petrol. Geol. 60:489-516) and Van Eysingia, F.W.B. 1975 (Geological time table, 3rd ed., Elsevier, Amsterdam).


EONS
ERAS PERIODS
EPOCHS
STAGES
PHANEROZOIC
PROTEROZOIC
ARCHAEOZOIC
Origin of Earth
CENOZOIC
MESOZOIC
PALEOZOIC
QUATERNARY
TERTIARY
CRETACEOUS
JURASSIC
TRIASSIC
PERMIAN
CARBONIFEROUS
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
UPPER CRETACEOUS
DANIAN
MAASTRICHTIAN
CAMPANIAN
Scale in 10^9 years before present
Scale in 10^8 years before present
Scale in 10^7 years before present

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