(24), and this places strong restrictions on the greenhouse components required by (6, 22, 23). Continued progress in our understanding of the history of the terrestrial atmosphere and the paleoclimate over time scales exceeding 10^9 years will indicate whether these complex models are correct and dramatic atmospheric evolution has fortuitously offset the reduced solar power input to the planet in the past [or perhaps that the Gaian or biological thermostat (22) has been operative]. Regarding the astrophysical aspects of the problem, if compensating effects such as those found by Hart (23) are ruled out, then the general nature of the predicted increase of the solar luminosity suggests that the study of stellar structure will be presented with a problem even more fundamental than is the solar neutrino dilemma.

MICHAEL J. NEWMAN*

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena 91125

ROBERT T. ROOD

Department of Astronomy, University of Virginia, Charlottesville 22903

References and Notes

1. H. Zirin and J. Walter, Eds., *Proceedings of the Workshop: The Solar Constant and the Earth's Atmosphere* (Big Bear Solar Observatory, Big Bear, Calif., 19–21 May 1975).
2. L. P. Knauth and S. Epstein, *Geochim. Cosmochim. Acta* **40**, 1095 (1976).
3. M. I. Budyko, *Tellus* **21**, 611 (1969); E. Eriksson, *Meteorol. Monogr.* **8**, 68 (1968); M. C. MacCracken and G. L. Potter, Lawrence Livermore Laboratory preprint UL RL-76132 (1975); S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **24**, 241 (1967); S. H. Schneider and T. Gal-Chen, *J. Geophys. Res.* **78**, 6182 (1973); W. D. Sellers, *J. Appl. Meteorol.* **8**, 392 (1969).
4. G. R. North, *J. Atmos. Sci.* **32**, 1301 (1975).
5. R. K. Ulrich, *Science* **190**, 619 (1975).
6. C. Sagan and G. Mullen, *ibid.* **177**, 52 (1972).
7. J. I. Katz, unpublished work cited in (6).
8. C. Emiliani and N. J. Shackleton, *Science* **183**, 511 (1974).
9. R. A. Lyttleton and F. Hoyle, *Proc. Cambridge Philos. Soc.* **35**, 405 (1939); F. W. W. Dilke and D. O. Gough, *Nature (London)* **240**, 262 (1972); W. H. McCrea, *ibid.* **255**, 607 (1975); R. J. Talbot, Jr., D. M. Butler, M. J. Newman, *ibid.* **262**, 561 (1976).
10. M. Schwarzschild, *Structure and Evolution of the Stars* (Princeton Univ. Press, Princeton, N.J., 1958).
11. R. Davis and J. M. Evans, *Bull. Am. Phys. Soc.* **21**, 683 (1976).
12. R. H. Dicke, *Science* **138**, 653 (1962).
13. P. Pochoda and M. Schwarzschild, *Astrophys. J.* **139**, 587 (1964).
14. I. W. Roxburgh, *Nature (London)* **261**, 301 (1976).
15. I. I. Shapiro and R. D. Reasenberg, paper presented at the International Symposium on Experimental Gravitation, Pavia, Italy, 17–20 September 1976.
16. T. C. van Flandern, *Mon. Not. R. Astron. Soc.* **170**, 333 (1975).
17. E. B. Fomalont and R. A. Sramek, *Astrophys. J.* **199**, 749 (1975).
18. D. R. Mikkelsen and J. M. Newman, *Phys. Rev. D*, in press.
19. R. T. Rood and R. K. Ulrich, *Nature (London)* **252**, 366 (1974).
20. J. D. Hays, J. Imbrie, N. J. Shackleton, *Science* **194**, 1121 (1976).
21. D. L. Turcotte, J. L. Cisne, J. C. Nordmann, *Icarus* **30**, 254 (1977).
22. L. Margulis and J. E. Lovelock, *ibid.* **21**, 471 (1974).
23. M. H. Hart, *ibid.*, in press. In more recent work in preparation, Hart has found the remarkable result that, far from being in conflict with his climate model, an increasing solar luminosity is actually required to produce a habitable earth.
24. P. E. Cloud, Jr., *Science* **160**, 729 (1968).
25. J. N. Bahcall, W. F. Huebner, N. H. Magee, A. L. Mertz, R. K. Ulrich, *Astrophys. J.* **184**, 1 (1973).
26. R. K. Ulrich and R. T. Rood, *Nature (London) Phys. Sci.* **241**, 111 (1973).
27. M. J. Newman and W. A. Fowler, *Astrophys. J.* **207**, 601 (1976).
28. D. D. Clayton, M. J. Newman, R. J. Talbot, Jr., *ibid.* **201**, 489 (1975).
29. M. J. Newman and W. A. Fowler, *Phys. Rev. Lett.* **36**, 895 (1976).
30. D. D. Clayton, E. Dwek, M. J. Newman, R. J. Talbot, Jr., *Astrophys. J.* **199**, 494 (1976).
31. M. J. Newman and R. J. Talbot, Jr., *Nature (London)* **262**, 559 (1976).
32. We are grateful to W. A. Fowler for bringing the problem to our attention, to R. K. Ulrich, I. W. Roxburgh, and M. H. Hart for helpful discussions, and to R. Davis, G. Verschuur, and R. H. Dicke for pointing out references. This work was supported in part by NSF grant PHY76-83685.

* Present address: Max Planck Institute for Astrophysics, Munich, West Germany.

31 May 1977; revised 25 August 1977

High Pressures on Small Areas

Abstract. *Small diamond indentors with spherical tips were pressed against a polished diamond flat. Pressures were calculated from Hertz contact theory. Very high pressures were achieved on small areas.*

As Hertz first showed, high pressures can be generated when a sphere is pressed against a flat (1). In our experiments single crystals of diamond were used for both the spherical tip and the flat anvil (Fig. 1).

The contact pressure that develops when an indentor with a spherical tip is pressed against a flat plate is given by

$$P_0 = \left(\frac{3}{2}\right)^{1/3} \pi^{-1} \left(\frac{E}{1-\nu^2}\right)^{2/3} R^{-2/3} F^{1/3} \qquad (1)$$

where P_0 is the contact pressure at the center, F is the applied force, E is Young's modulus, ν is Poisson's ratio, and R is the radius of the indentor (2). In this relation it is assumed that the contact radius is small as compared to R and that linear elasticity is valid.

Several small diamond indentors with spherical tips ranging in radius from 2 to 20 μm were pressed against a highly polished diamond flat [E = 11.41 Mbar and ν = 0.07 (3)]. On the basis of Eq. 1, pressures as summarized in Table 1 were obtained. After a given load was removed, both the anvil and the indentor were examined carefully. High-magnification photographs were made of the indentor profile at different known rotations and these were carefully compared with the profiles for the same rotations prior to loading. Also direct photographs of the tip end obtained by viewing along the axis were made. By these techniques the onset of permanent deformation could be observed.

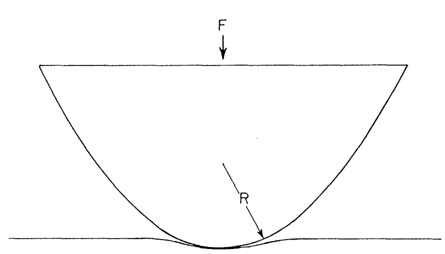

Fig. 1. Diagram of a spherically tipped diamond indentor of radius R pressed against an initially flat diamond anvil with a force F. Typically the indentor is a single crystal diamond 1/500 to 1/1000 carat with a tip radius of 2 to 20 μm, and it is mounted in a steel shank. The flat is single crystal diamond (about ½ carat) with parallel faces, also mounted in a steel shank. Because of the small size of the indentor, the damage to the flat is quite local and many tests can be made on the same flat if different areas are used.

There are three possible modes of failure. The diamond may fracture, plastically deform, or undergo a phase transformation. Usually failure occurred by a definite ring crack on the flat diamond. Observations were made with a Reichert optical microscope equipped with Nomarski interference contrast. As the indentor radius decreased, higher pressures were obtainable before fracture. We have found (for a radius range of 400 to 20 μm) that the pressure at which fracture occurs on a (100) face follows the equation

$$P_0^{\mathrm{f}} = \left(\frac{2.4}{R}\right)^{1/3} \qquad (2)$$

where P_0^{f} is the peak pressure (in megabars) at which fracture occurs and R is in micrometers. This type of behavior is in keeping with the general trend of Auerbach's law (4). For R = 2 μm, the pre-

Table 1. Results of pressure measurements.

Radius of tip (μm)	Highest P_0 without failure (Mbar)	P_0 with failure (Mbar)	Comment
20	0.9	1.0	Ring crack
8	1.0	1.2	Ring crack
6.5	1.2	1.3	Ring crack
2.5	1.2	1.4	Tip and flat fractured
2	1.4	1.6	Failure mode not determined*

*Possible failure modes include (i) fracture or ring crack, (ii) plastic deformation, and (iii) phase transformation.

dicted center pressure at fracture is $P_0^f = 1.9$ Mbar. Thus, to postpone fracture, a tip with the smallest possible radius should be used.

To obtain very high pressures, yielding must also be postponed. The compressive yield strength of bulk diamond is approximately 350 kbar (*5*). From Hertz contact theory the center pressure at which yielding of diamond occurs is 1.36 times the compressive yield strength; thus for bulk diamond a pressure of approximately 500 kbar can be reached without yielding (*5*). However, there is evidence that a material may approach the strength of a perfect crystal as the spherical tip size becomes very small (*6*). This behavior apparently results because of the lack of dislocations in a very tiny volume. For example, with $R = 2$ μm and $P_0 = 1.5$ Mbar, the radius of the contact area is only 0.8 μm. The region with high shear stresses in either the anvil or indentor is therefore only about 1 μm³ or 10^{-12} cm³. With a dislocation density of 10^6 cm per cubic centimeter in diamond, the probability of finding a dislocation is very small. Thus with tiny tips, essentially perfect diamond is being used. For perfect diamond Ruoff (*5*) has predicted an attainable pressure before yielding of 1.8 Mbar for [100] loading. In the same pressure range Van Vechten (*7*) has predicted a phase transformation for diamond at 1.7 Mbar. As noted above, fracture is expected for a tip with $R = 2$ μm when P_0 reaches 1.9 Mbar. Thus all three of these failure modes are expected at approximately the same pressure. At the present time, we have not resolved which of the three possible failure modes has occurred for the smallest tip size.

The calculated pressures without failure in Table 1 should be reasonably good values. The radius of the indentor can be determined to within 10 percent (the pressure is thus known to within 7 percent). The stress-strain curves of germanium and silicon (which also have the diamond cubic structure) have been accurately calculated from the accurate second- and third-order elastic constants. For [100] compressive loading they are nearly linear for compressive strains to 0.15 (*8*), and for [111] compressive loading for strains to 0.20 (*5*). Similar behavior is expected for diamond where a compressive strain of 0.15 corresponds to a compressive stress of 1.7 Mbar. Thus the linear diamond scale used here has a good scientific basis. Moreover, when this technique of generating pressures is combined with the microelectronics fabrication technology recently applied by Ruoff and Chan (*9*) to high pressure research, it will be possible to carry out scientific experiments under these ultrapressure conditions.

A. L. RUOFF
J. WANAGEL

Department of Materials Science and Engineering, Cornell University, Ithaca, New York 14853

References and Notes

1. H. Hertz, *J. Math. (Crelle)* **92**, 156 (1881).
2. S. Timoshenko, *Theory of Elasticity* (McGraw-Hill, New York, 1970), pp. 409–413; A. L. Ruoff and K. S. Chan, *J. Appl. Phys.* **47**, 5080 (1976).
3. H. J. McSkimin and P. Andreatch, Jr., *J. Appl. Phys.* **43**, 2944 (1972).
4. F. Auerbach, *Ann. Phys. Chem.* **43**, 61 (1891).
5. A. L. Ruoff, paper presented at the 6th AIRAPT (Association Internationale for Research and Advancement of High Pressure Science and Technology) International High Pressure Conference, Boulder, Colo., July 1977; *Cornell Univ. Mater. Sci. Cent. Rep. 2855* (1977).
6. J. J. Gilman, *Acta Metall.* **7**, 608 (1959); N. Gane and F. P. Bowden, *J. Appl. Phys.* **39**, 1432 (1968).
7. J. A. Van Vechten, *Phys. Rev. B* **7**, 1479 (1973).
8. A. L. Ruoff, *J. Appl. Phys.*, in press.
9. _____ and K. S. Chan, paper presented at the 6th AIRAPT (Association Internationale for Research and Advancement of High Pressure Science and Technology) International High Pressure Conference, Boulder, Colo., July 1977; *Cornell Univ. Mater. Sci. Cent. Rep. 2854* (1977).
10. This research was carried out under NASA grant NGR 33-010-189. This work was also supported through the use of the facilities of the Cornell Materials Science Center, which are sponsored by the National Science Foundation.

25 July 1977; revised 28 September 1977

Immunofluorescence Localization of Proteins of High Molecular Weight Along Intracellular Microtubules

Abstract. *To help clarify the role, in cytoplasmic microtubule function, of the proteins of high molecular weight that coassemble with tubulin in vitro, a monospecific antibody against the proteins of high molecular weight was prepared from the serum of immunized rabbits by affinity chromatography. With indirect immunofluorescence we found that the protein in both cultured neuroblastoma cells and 3T3 cells is distributed in an extensive filamentous array that originates at sites near the nucleus and extends to the cell periphery or, in neuroblastoma cells, gathers into bundles which enter neurites. No filaments were seen with nonspecific antibodies from serum taken before immunization, and prior incubation of the specific antibody with purified protein of high molecular weight (but not tubulin) prevented filament visualization. The filamentous pattern in 3T3 cells was disrupted by colchicine. This evidence indicates that the proteins of high molecular weight are found in cells in association with cytoplasmic microtubules.*

Two major proteins are consistently found in various preparations of cytoplasmic microtubules (*1*, *2*). One is tubulin, which assembles to form the microtubule backbone and usually constitutes more than 80 percent of the total protein. The other is a protein of higher molecular weight (composed of two subunits each greater than 300,000 daltons), the function of which is unclear. In cilia and flagella an adenosine triphosphatase of high molecular weight, called dynein (*3*), forms side arms which project from the A subfiber of each outer doublet microtubule onto the B subfiber of the adjacent doublet. This protein provides the energy for sliding between adjacent outer doublets that is responsible for the movement of these organelles (*3*, *4*). Similar side arms or filamentous material are seen by electron microscopy in association with microtubules derived from brain extracts by repetitive cycles of assembly and disassembly. These structures, which are probably composed of the proteins of high molecular weight (*5*), have not yet been shown to have adenosine triphosphatase activity.

The above observations suggest that the proteins of high molecular weight associated with microtubules assembled in vitro from crude brain extracts may be

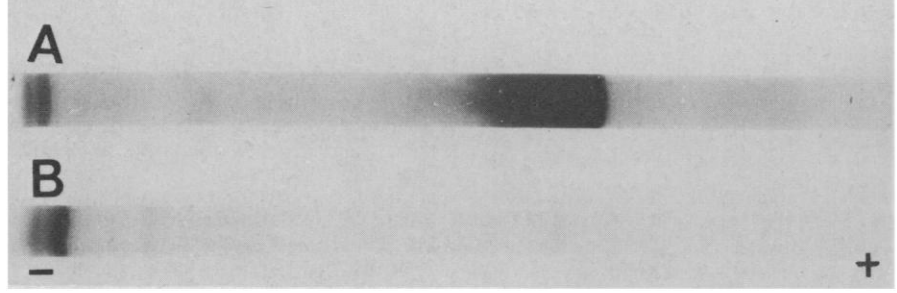

Fig. 1. Sodium dodecyl sulfate–polyacrylamide gel electrophoresis of purified MAP and 2× microtubule protein. Approximately 25 μg of MAP (left) or 150 μg of 2× microtubule protein (right) was applied. Gels were stained with Coomassie brilliant blue.