Vol 446 | 5 April 2007 | doi:10.1038/nature05667

Geomagnetic field strength 3.2 billion years ago recorded by single silicate crystals

John A. Tarduno[1,2], Rory D. Cottrell[1], Michael K. Watkeys[3] & Dorothy Bauch[1]

The strength of the Earth's early geomagnetic field is of importance for understanding the evolution of the Earth's deep interior, surface environment and atmosphere. Palaeomagnetic and palaeointensity data from rocks formed near the boundary of the Proterozoic and Archaean eons, some 2.5 Gyr ago, show many hallmarks of the more recent geomagnetic field. Reversals are recorded[1], palaeosecular variation data[2] indicate a dipole-dominated morphology and available palaeointensity values are similar to those from younger rocks[1–3]. The picture before 2.8 Gyr ago is much less clear. Rocks of the Archaean Kaapvaal craton (South Africa) are among the best-preserved, but even they have experienced low-grade metamorphism[4]. The variable acquisition of later magnetizations by these rocks is therefore expected, precluding use of conventional palaeointensity methods. Silicate crystals from igneous rocks, however, can contain minute magnetic inclusions capable of preserving Archaean-age magnetizations. Here we use a CO_2 laser heating approach and direct-current SQUID magnetometer measurements to obtain palaeodirections and intensities from single silicate crystals that host magnetite inclusions. We find 3.2-Gyr-old field strengths that are within 50 per cent of the present-day value, indicating that a viable magnetosphere sheltered the early Earth's atmosphere from solar wind erosion.

Néel's[5] theory can be used to derive time–temperature relationships that are useful for predicting the acquisition of thermoviscous magnetization. According to this theory, the thermal relaxation time τ for single-domain magnetic grains can be expressed as[6]:

$$\frac{1}{\tau} = \frac{1}{\tau_0}\exp\left[-\frac{\mu_0 V M_s H_K}{2kT}\left(1-\frac{|H_0|}{H_K}\right)^2\right] \quad (1)$$

where τ_0 (10^{-9} s) is the interval between thermal excitations, μ_0 is the permeability of free space, V is grain volume, M_s is spontaneous magnetization, k is Boltzmann's constant, T is temperature and H_0 is the applied field. The microcoercive force H_K measures the field needed to rotate the magnetization without thermal excitation[6]. Given $H_K \gg H_0$, and relaxation times τ_A and τ_B representing temperatures T_A and T_B, respectively, we can write[7]:

$$\frac{T_A \ln(\tau_A/\tau_0)}{M_s(T_A)H_K(T_A)} = \frac{T_B \ln(\tau_B/\tau_0)}{M_s(T_B)H_K(T_B)} \quad (2)$$

This relationship suggests that, for low-grade metamorphism occurring over 1 Myr, single-domain magnetic grains with blocking temperatures less than 400 °C could be contaminated by overprints (see Supplementary Information). For multidomain magnetic grains, we can expect to measure partial thermoviscous magnetizations at unblocking temperatures up to the Curie point of magnetite[6].

With increased temperatures, there is also potential for the growth of new magnetic minerals. For example, palaeointensities 4 to 10 times lower than present-day values have been reported from 3.5-Gyr-old lavas (the Komati Formation) of the Barberton greenstone belt[8]. The magnetization was originally thought to be a thermoremanent magnetization related to early greenschist metamorphism, but a subsequent study concluded it to be a chemical remanent magnetization related to magnetite grain growth[9]. Chemical remanent magnetizations provide only minimum bounds on field strength. Moreover, the Barberton area has also seen low-grade metamorphism in late Archaean[4], and possibly Proterozoic, times. The path to magnetic grain growth in iron-rich komatiites during metamorphism is direct, and the chemical remanent magnetization could be much younger than the rock age. Directions from whole-rock samples of 3.45-Gyr-old lavas of the Pilbara craton (Australia) have also been interpreted as a sign of an early dynamo[10]. However, these data lack field strength estimates and may also be contaminated by secondary magnetizations related to later metamorphism (see Supplementary Information).

The challenge was to find an alternative magnetic recorder that can see through the complex set of overprinted secondary magnetizations that should affect Archaean rocks through thermochemical processes. The acquisition of secondary magnetizations is related to magnetic domain state, so single-domain or pseudo-single-domain carriers needed to be isolated. In addition, we looked for samples with a minimum of iron that might otherwise migrate to form new magnetic minerals during metamorphism.

Magnetic properties of individual rock-forming silicate grains have been shown to be a valuable means of assessing palaeointensity and directions[11–13] because these crystals can contain single-domain and near-single-domain (pseudo-single-domain) magnetic inclusions protected by the silicate host. We applied this approach to the study of the Dalmein and Kaap Valley Plutons that intrude the Barberton greenstone belt. These are granodioritic and tonalitic, respectively, and both have been dated to 3.2 Gyr ago by U–Pb geochronology[14]. We focused on feldspar (microcline), quartz and hornblende. To investigate the promise of these mineral carriers, we first evaluated their rock magnetic properties. Isothermal remanent acquisition curves do not indicate the presence of high-coercivity magnetic inclusions such as haematite. Low-temperature data collected using a Magnetic Properties Measurement System show the variable presence of the Verwey transition[6]—the cubic to monoclinic phase transition in magnetite—on cooling through 120 K (Supplementary Fig. 1). These data indicate that all three crystal types can have magnetite inclusions. However, magnetic hysteresis properties measured using a Princeton Measurements Corporation alternating gradient force magnetometer define different mean magnetic domain states of the silicate-hosted inclusions. Hornblende has inclusions with near multidomain behaviour, whereas inclusions in quartz and microcline have pseudo-single-domain to single-domain characteristics (Supplementary Fig. 2). Because of its high overprint potential, we excluded hornblende from further consideration. Quartz and microcline did not display

[1]Department of Earth and Environmental Sciences, [2]Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA. [3]School of Geological Sciences, University of KwaZulu-Natal, Durban 4041, South Africa.

significant magnetic anisotropies (Supplementary Fig. 3), and are also attractive because they contain minimal amounts of reactive iron.

To test whether the isolated remanence was far removed from later field directions, we developed a new CO_2 laser heating approach to link palaeointensity data from single silicate crystals to directional components (see Supplementary Information). Our procedure begins with a variation of micro-sampling[15] that uses oriented thin sections cut from palaeomagnetic cores. The sections are much thicker than those used for standard petrographic studies (>1 mm). After undesirable minerals (for example, hornblende) are mechanically etched away, the sections are cut into smaller subsections, each having a single mineralogy. Each subsection holds a single grain with a length of ~2–3 mm, which is used for directional and Thellier palaeointensity analyses.

Subsections are demagnetized using a 20 W Synrad CO_2 laser, which yields a 10.6 μm infrared beam that couples well with silicates. Renne and Onstott[16] previously used a ruby laser to selectively demagnetize grains by ablation. Our approach differs in that the CO_2 laser is used to heat the crystals gently. Heating is carried out on timescales of a few minutes, minimizing total heating duration and potential thermally induced alteration while facilitating the measurement of oriented samples.

Testing and calibration were performed using infrared cameras and silicate crystals separated from younger rocks for which directional data were available (Supplementary Fig. 4). All remanence measurements were made using a 2 G direct-current superconducting quantum interference device (SQUID) magnetometer with a high-resolution coil configuration.

Quartz and microcline single crystals have stable remanence components at high unblocking temperatures after magnetizations at lower unblocking temperatures are removed (Fig. 1). This pattern is consistent with the predicted acquisition of overprints by magnetic grains with low unblocking temperatures (equations (1) and (2)) and the preservation of primary signals by grains with higher unblocking temperatures.

Undeformed mafic dykes ranging from Archaean to Mesozoic in age in the Dalmein and Kaap Valley Plutons are vertical, suggesting that the plutons have not undergone significant tilting since emplacement. We can use magnetic measurements from these dykes to test whether the silicate crystals preserve Archaean directions. A dyke from the Kaap Valley Pluton yields two components of magnetization (Supplementary Fig. 5): a steep component at intermediate unblocking temperatures (~200 °C to 450 °C); and a shallow high-unblocking-temperature component (500 °C to 580 °C). Thermomagnetic experiments (Supplementary Fig. 6) and scanning electron microscopy suggest that the shallow component is carried by magnetite formed during cooling (that is, high-temperature oxidation). It is similar to directions reported from dykes of the 1.1-Gyr-old Umkondo large igneous province[17]. However, the steep direction is similar to ~2-Gyr-old overprints previously reported from the Kaapvaal craton[18]. Given the rock magnetic characteristics of the dyke, and its geologic setting, it is unlikely that the intermediate-unblocking-component of magnetization is older than the component isolated at higher unblocking temperatures. Therefore, the shallow component is either older than 2.0 Gyr, or the steep direction is a combination of several later magnetizations (and thus not a true reflection of the magnetic field 2.0 Gyr ago) (Fig. 2). A dyke from the Dalmein Pluton also carries a high-unblocking-temperature component, but its direction suggests the dyke is related to Karoo magmatism[19] 180 Myr ago.

The derived palaeomagnetic directions from the silicate minerals (Fig. 2): (1) agree between plutons; (2) differ from the directions of younger intruding dykes (Supplementary Tables 1 and 2); and (3) record dual polarity (Kaap Valley Pluton). The data from the Kaap Valley Pluton hint at some polarity asymmetry, but we cannot determine from the available data whether this reflects incomplete sampling of a time-varying field, or a longer-term non-dipole morphology. However, the directions preserved by the Kaap Valley Pluton quartz and feldspar clearly differ from those of a prior study of whole rocks[20], which were thought to record a pulse of rapid (>16 mm yr^{-1}) Archaean plate motion[21]. We feel that directions from the hornblende-rich whole rocks of the Kaap Valley Pluton instead reflect various extents of overprinting (equations (1) and (2)).

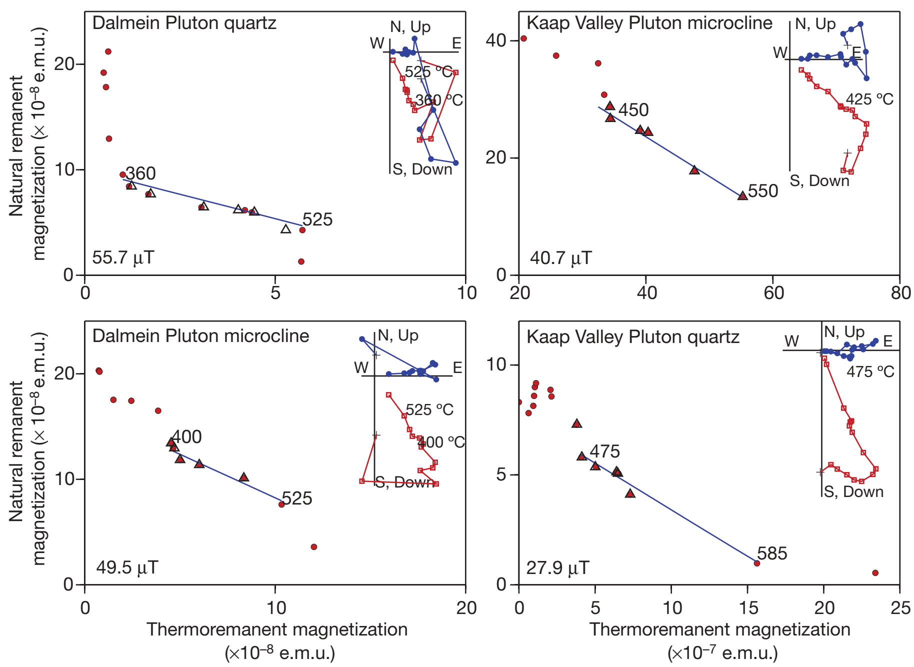

Figure 1 | Examples of natural remanent magnetization versus thermoremanent magnetization data from Thellier experiments on Archaean oriented single silicate crystals using a CO_2 laser/SQUID system. Triangles are partial-thermoremanent magnetization experimental checks (see ref. 12). The line is the least-squared fit to natural remanent magnetization versus thermoremanent magnetization data (circles); the resulting field estimate in μT is shown. Inset of each plot shows orthogonal vector plot of field-off steps used to constrain palaeomagnetic directions. Red squares, inclination; blue circles, declination.

Palaeointensity data that meet acceptance criteria[12] yield 21 raw field values between approximately 20 μT and 60 μT (Supplementary Tables 1 and 3). Because previous palaeointensity results from the Barberton komatiite lavas record a chemical remanent magnetization[9] of uncertain age (but potentially as young as 2.8 Gyr[22], Fig. 2), the new data represent the earliest direct measurement of Earth's magnetic field strength. There is agreement between values obtained from quartz and microcline, and between results obtained using laser and conventional heating (Supplementary Table 3). Together with the directional data, these values suggest virtual dipole moments of $7.5 \pm 1.2 \times 10^{22}$ A m^2 and $6.4 \pm 2.1 \times 10^{22}$ A m^2 for the Dalmein and Kaap Valley Plutons, respectively. Both estimates are similar to the present field strength.

Cooling rates in nature vary greatly from those of our experiments, so we examine cooling rate corrections[23] using geochronological and geological constraints (see Supplementary Information). These corrections suggest that the raw values could overestimate the strength by 47% to 57%. A limitation of the corrections is their reliance on theoretical considerations of elongate single-domain grains. The effect on pseudo-single-domain grains, for example, is likely to be much less[24]. Nevertheless, applying the corrections can yield useful lower bounds on field strength. The corrected virtual dipole moment from the Dalmein Pluton is $4 \pm 1 \times 10^{22}$ A m^2, whereas the corrected value from the Kaap Valley Pluton is $3 \pm 1 \times 10^{22}$ A m^2. We note that the lower bound from the Kaap Valley Pluton is within 50% of the value[25] thought to characterize the Brunhes chron (0–0.78 Myr ago), whereas the lower bound for the Dalmein Pluton value is within 50% of the intensity of the present-day field. The present-day dipole field is rapidly losing strength[26]; if it falls to half its current value, non-dipole foci will emerge, allowing deeper penetration of highly energetic solar particles into the atmosphere[27]. However, the overall field will remain relatively strong, maintaining a significant magnetosphere. Therefore, on the basis of the lower bounds of field strength provided by our new data, we expect that a magnetosphere would have sheltered the early Archaean Earth from solar-wind-related atmospheric erosion.

The geodynamo could have commenced more than 1 Gyr earlier than the new records available from the Kaapvaal craton silicate minerals, with formation of the liquid iron core shortly after planetary accretion. However, this contrasts with a recent inference based on the abundance and isotopic ratio of nitrogen in lunar soils. These suggest a ~3.8–3.9-Gyr-old terrestrial source, eroded from Earth's atmosphere by the solar wind[28] in the absence of a strong magnetic field and magnetosphere. If the hypothesis for the origin of lunar nitrogen is correct, our direct palaeo-field measurements constrain the start of the dynamo to between 3.9 and 3.2 Gyr ago. This is a later start than on Mars, where magnetic anomalies from terrains older than ~4 Gyr reflect a past dynamo[29]. Earth's dynamo may have started because the onset of solid inner-core growth resulted in a change from stratified to convective core flow. Recent considerations suggest that an inner-core age this old is compatible with available compositional and thermal constraints[30]. The smaller size and faster cooling of Mars relative to Earth, together with differences in its accretionary history, may have led to either an earlier initiation of inner-core growth, or direct stimulation of liquid-core convection. Either mechanism could have driven an earlier, but ultimately unsustainable, Martian dynamo.

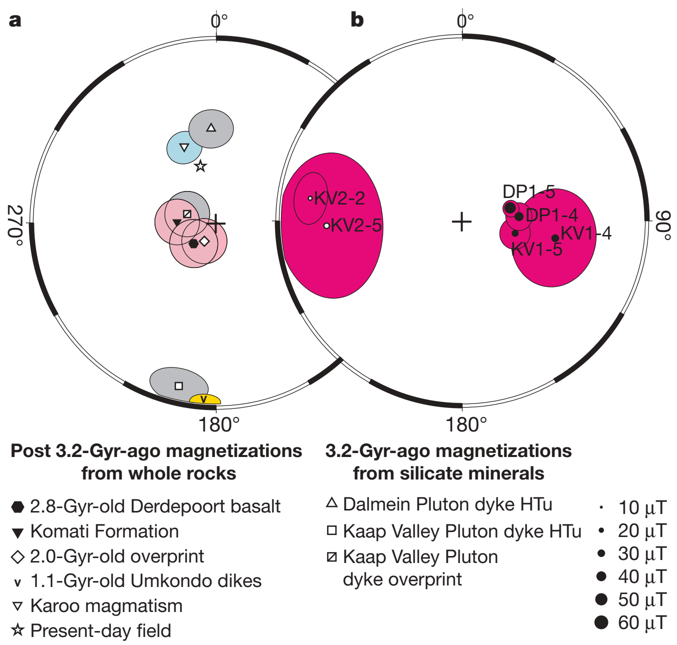

Figure 2 | Stereonets showing palaeomagnetic and palaeointensity results from the Kaapvaal craton, South Africa. Filled symbols, positive inclinations; open symbols, negative inclinations. **a**, Post 3.2-Gyr-ago directions from whole rocks with 95% confidence intervals (grey) with directions predicted for the Barberton area using Mesozoic–Archaean palaeomagnetic poles (colours are keyed to age: magenta, 3.2 Gyr; pink, Archaean–Proterozoic; yellow, Proterozoic; blue, Jurassic; grey, unknown age). HTu, high-unblocking-temperature component. The Kaap Valley Pluton dyke overprint is the component isolated at intermediate unblocking temperatures. Data sources for other directions: Derdepoort basalt, ref. 22; Komati Formation, ref. 9; the 2.0-Gyr-old overprint, ref. 18; Umkondo dykes, ref. 17; Karroo magmatism, ref. 19. **b**, Results from oriented quartz and microcline crystals. Symbol size represents intensity; 95% confidence regions around the mean direction are also shown (magenta). DP, Dalmein Pluton silicate crystal (quartz and feldspar) means; KV, Kaap Valley Pluton silicate crystal (quartz and feldspar) means. Labels refer to samples/sites (see Supplementary Information Tables).

Received 30 November 2006; accepted 7 February 2007.

1. Dunlop, D. J. & Yu, Y. in *Timescales of the Paleomagnetic Field* (eds Channell, J. E. T., Kent, D. V., Lowrie, W. & Meert, J. G) 85–100 (Geophys. Monograph Ser. 145, American Geophysical Union, Washington DC, 2004).
2. Smirnov, A. V. & Tarduno, J. A. Secular variation of the Late Archean–Early Proterozoic geodynamo. *Geophys. Res. Lett.* **31,** L16607 (2004).
3. Smirnov, A. V., Tarduno, J. A. & Pisakin, B. N. Paleointensity of the Early Geodynamo (2.45 Ga) as recorded in Karelia: a single crystal approach. *Geology* **31,** 415–418 (2003).
4. Tice, M. M., Bostick, B. C. & Lowe, D. R. Thermal history of the 3.5–3.2 Ga Onverwacht and Fig Tree Groups, Barberton greenstone belt, South Africa, inferred by Raman microspectroscopy of carbonaceous material. *Geology* **32,** 37–40 (2004).
5. Néel, L. Some theoretical aspects of rock magnetism. *Adv. Phys.* **4,** 191–243 (1955).
6. Dunlop, D. J. & Özdemir, Ö. *Rock Magnetism, Fundamentals and Frontiers* (Cambridge Univ. Press, Cambridge, UK, 1997).
7. Pullaiah, G., Irving, E., Buchan, K. L. & Dunlop, D. J. Magnetization changes caused by burial and uplift. *Earth Planet. Sci. Lett.* **28,** 133–143 (1975).
8. Hale, C. J. The intensity of the geomagnetic field at 3.5 Ga: Paleointensity results from the Komati Formation, Barberton Mountain Land, South Africa. *Earth Planet. Sci. Lett.* **86,** 354–364 (1987).
9. Yoshihara, A. & Hamano, Y. Paleomagnetic constraints on the Archean geomagnetic field intensity obtained from komatiites of the Barberton and Belingwe greenstone belts, South Africa and Zimbabwe. *Precambr. Res.* **131,** 111–142 (2004).
10. McElhinny, M. W. & Senanayake, W. E. Paleomagnetic evidence for the existence of the geomagnetic field at 3.5 Ga Ago. *J. Geophys. Res.* **85,** 3523–3528 (1980).
11. Cottrell, R. D. & Tarduno, J. A. Geomagnetic paleointensity derived from single plagioclase crystals. *Earth Planet. Sci. Lett.* **169,** 1–5 (1999).
12. Cottrell, R. D. & Tarduno, J. A. In search of high fidelity geomagnetic paleointensities: A comparison of single crystal and whole rock Thellier-Thellier analyses. *J. Geophys. Res.* **105,** 23,579–23,594 (2000).
13. Tarduno, J. A., Cottrell, R. D. & Smirnov, A. V. The paleomagnetism of single silicate crystals: Recording geomagnetic field strength during mixed polarity intervals, superchrons and inner core growth. *Rev. Geophys.* **44,** RG1002, doi:10.1029/2005RG000189 (2006).
14. Poujol, M., Robb, L. J., Anhaeusser, C. R. & Gericke, B. A review of the geochronological constraints on the evolution of the Kaapvaal Craton, South Africa. *Precambr. Res.* **127,** 181–213 (2003).
15. Geissman, J. W., Harlan, S. S. & Brearley, A. J. The physical isolation and identification of carriers of geologically stable remanent magnetization: Paleomagnetic and rock magnetic microanalysis and electron microscopy. *Geophys. Res. Lett.* **15,** 479–482 (1988).

16. Renne, P. R. & Onstott, T. C. Laser-selective demagnetization: A new technique in paleomagnetism and rock magnetism. *Science* **242,** 1152–1155 (1988).
17. Gose, W. A., Hanson, R. E., Dalziel, I. W. D., Pancake, J. A. & Seidel, E. K. Paleomagnetism of the 1.1 Ga Umkondo large igneous province in southern Africa. *J. Geophys. Res.* **111,** B09101 (2006).
18. Layer, P. W., Lopez-Martinez, M., Kroner, A., York, D. & McWilliams, M. Thermochronometry and palaeomagnetism of Archaean Nelshoogte Pluton, South Africa. *Geophys. J. Int.* **135,** 129–145 (1998).
19. Hargraves, R. B., Rehacek, J. & Hooper, P. R. Palaeomagnetism of the Karoo igneous rocks in southern Africa. *S. Afr. J. Geol.* **100,** 195–212 (1997).
20. Layer, P. W., Kroner, A. & McWilliams, M. An Archean geomagnetic reversal in the Kaap Valley pluton, South Africa. *Science* **273,** 943–946 (1996).
21. Kroner, A. & Layer, P. W. Crust formation and plate motion in the early Archean. *Science* **256,** 1405–1411 (1992).
22. Wingate, M. T. D. A palaeomagnetic test of the Kaapvaal-Pilbara (Vaalbara) connection at 2.78 Ga. *S. Afr. J. Geol.* **101,** 257–274 (1998).
23. Halgedahl, S. L., Day, R. & Fuller, M. The effect of cooling rate on the intensity of weak-field TRM in single-domain magnetite. *J. Geophys. Res.* **85,** 3690–3698 (1980).
24. McClelland Brown, E. Experiments on TRM intensity dependence on cooling rate. *Geophys. Res. Lett.* **11,** 205–208 (1984).
25. Valet, J. P. Time variations in geomagnetic intensity. *Rev. Geophys.* **41,** 1004 (2003).
26. Hulot, G., Eymin, C., Langlais, B., Mandea, M. & Olsen, N. Small-scale structure of the geodynamo inferred from Oersted and Magsat satellite data. *Nature* **416,** 620–623 (2002).
27. Sinnhuber, M. *et al.* A model study of the impact of magnetic field structure on atmospheric composition during solar proton events. *Geophys. Res. Lett.* **30,** 1818 (2003).
28. Ozima, M. *et al.* Terrestrial nitrogen and noble gases in lunar soils. *Nature* **436,** 655–659 (2005).
29. Stevenson, D. J. Mars' core and magnetism. *Nature* **412,** 214–219 (2001).
30. Gubbins, D., Alfe, D., Masters, G., Price, G. D. & Gillan, M. Gross thermodynamics of two-component core convection. *Geophys. J. Int.* **157,** 1407–1414 (2004).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank P. Layer, A. Smirnov and P. Doubrovine for discussions. This research was supported by NSF.

Author Contributions J.A.T., M.K.W. and D.B. took part in field studies, and J.A.T., R.D.C. and D.B. in technique development, experiments and data analysis.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to J.A.T. (john@earth.rochester.edu).