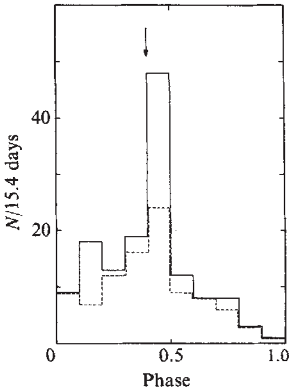

Fig. 3 Number of flares, *N*, per phase bin, folded by a period of 154 days (full line) and number of active regions contributing flares (dashed line). The absolute times of phase 0.4 (arrow) are: 1980 May 26; 1980 October 27; 1981 March 30; 1981 September 1; 1982 February 2; 1982 July 6; 1982 December 8; 1983 May 12.

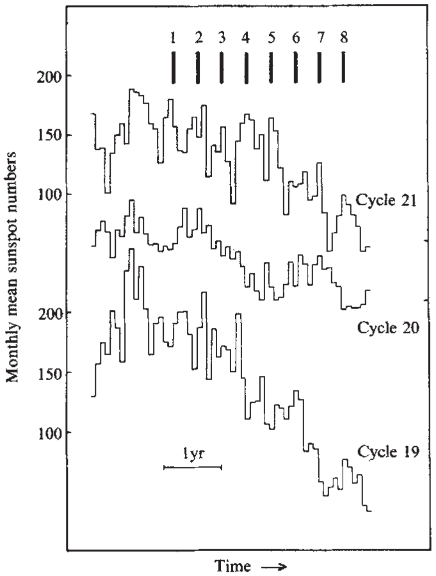

Fig. 4 Monthly mean unsmoothed sunspot number during the declining phases of cycles 19–21 (ref. 4). The cycles were aligned arbitrarily in time with their absolute maxima. The bars at the top of the figure mark the times with respect to cycle 21 when the eight bursts of high-energy flare activity occurred.

in time from 3 months to 1 yr, with an average duration of 5 months. The most extensive analysis of the monthly mean sunspot number was carried out by Wolff[11] who searched for significant frequencies using a 230-yr data base from 1749 to 1979 and found a set ranging from 15 to 180 nHz. He interprets these as the beat frequencies of the rotation rate of g-modes. (The g-modes are thought to be oscillations of the solar interior.) The most prominent period of <200 days found by Wolff is 155.4 days (74.49 nHz), which is close to what we have found for energetic solar flares.

Thus there is clear and compelling evidence for a 154-day regularity or periodicity in the occurrence of energetic flares. This effect was first recognized and measured for flares producing emissions of >300 keV and has been confirmed for flares producing soft X rays. The latter data set was obtained from multiple satellites having ~100% solar coverage and hence removes the possibility of any orbital selection effects. This regularity is not a minor effect involving only a few flares but, in fact, involves >30% of all the flares observed. The nature of this 154-day period is not yet understood but may have its origin in deeper layers of the Sun. If so, a better understanding will not only provide information on solar flare production but will be an important probe of subphotospheric phenomena. It will be interesting to see whether the recurrence period observed for energetic photon flares (>300 keV) persists throughout the remainder of the SMM post-repair mission.

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Magnetic field amplification in the solar nebula through interaction with the T-Tauri wind

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As carbonaceous chondrites are the least thermally-evolved and hence the most primitive of the meteorites, their residual magnetization can, in principle, be used to estimate the intensity of the magnetic field in the primordial solar nebular, which varies between 0.2 and 1 G (refs 1–4), and could be as high as 2–3 G (ref. 4). The presence of palaeomagnetic fields of such magnitude is of importance in reconstructing the early history of the Solar System and of planetary formation. Levy and Sonnet[5], for example, have stressed this point in comparing the respective merits of four alternative sources of the primordial magnetic field. They claim only two of these are possible: (1) a large solar magnetic field spread into the solar nebula; (2) a hydromagnetic dynamo field generated in the solar nebula itself. We show here that there is in fact a further possibility that fits the requirements for strong magnetic field generation and energetic particle irradiation of the grains[6]: magnetic field enhancement at the point of stagnation between the solar nebula and the intense solar outflows. This mechanism, which involves the interaction of the T-Tauri wind with the solar nebular, is straightforward and is supported by results from recent space research.

We argue basically that during the brief period ($\approx 10^5$–10^6 yr) of the T-Tauri phase of the proto-Sun, the solar nebula was being swept up by an intense solar wind with a mass-loss rate of $\mathrm{d}M/\mathrm{d}t \approx 10^{-7}$–$10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ (refs 7, 8). This was accompanied by strong flare activities[7,9] which contributed to the grain irradiation effect. However, the penetration of solar particles should at first be limited only to the inner edge and the boundary layers of the solar nebula (Fig. 1). This scenario is compatible with Wetherill's idea[10] that, because of the blocking effect, the condensed grains forming Venus should be subjected to much more severe effects of primordial solar wind by implantation (^{20}Ne and ^{36}Ar, say) than those later forming the Earth. However, we require that the 'working surface' or the stagnation point between the T-Tauri wind and the inner edge of the solar nebula should progress outward to reach the condensation zone of the carbonaceous chondrites (that is, a solar distance ≈ 3 AU?).

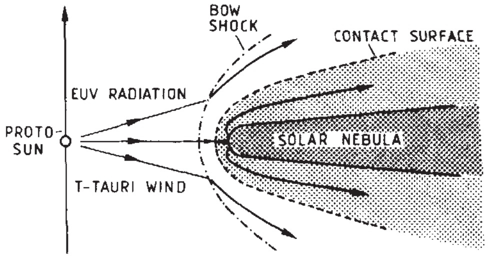

Fig. 1 A schematic view (not to scale) of the interaction process between the solar nebula and the T-Tauri wind of the early Sun. We postulated that, at the stagnation point between the solar wind and the solar nebula, the interplanetary magnetic field would be amplified to 0.1–2 G. Further leakage of the draped fields into the solar nebula would lead to magnetization of the condensed grains. EUV = extreme ultraviolet.

It is not known whether the solar nebula was clear of gas during the T-Tauri phase. In any event, even if there were little gas in the dust disk, the sputtering effect of the flare particles should be effective in generating a gas cloud. The subsequent ionization effect of the solar UV radiation and the charge-exchange process between the T-Tauri wind and the neutral gas will lead to a situation similar to that of solar wind interaction with comets, or Venus, in which the interplanetary magnetic fields are compressed (or draped) ahead of the ionospheres of these planetary bodies[11].

Interplanetary magnetic fields (flux $B_\infty \approx 1\times10^{-4}$ G), as demonstrated by the Pioneer Venus observations[12], are piled ahead of the contact surface separating the ionosphere of Venus and the shocked solar wind. The amplification effect can be approximated by equating the magnetic field pressure to the ram pressure of the solar wind. A similar relation has been used to estimate the interplanetary magnetic field piled ahead of a cometary ionosphere[13], and detailed magnetohydrodynamic calculations[14–16] have shown that the Lorentz force due to the radius of curvature of the captured field lines will be important, and will lead to further enhancement of the magnetic field. That is, if B_i is the peak field flux at the stagnation point, it could be given by

$$\frac{B_i^2}{8\pi} \approx (2\text{–}3)\rho_\infty V_\infty^2 \qquad (1)$$

where ρ_∞ and V_∞ are the mass density and speed of the solar wind at large upstream distances, respectively. In the case of the T-Tauri wind, with $\mathrm{d}M/\mathrm{d}t \approx 10^{-7}\text{–}10^{-6}\, M_\odot\,\mathrm{yr}^{-1}$, a wind speed $(V) = 200\ \mathrm{km\,s}^{-1}$, and a solar distance of ~3 AU from the proto-Sun, the application of equation (1) indicates that the magnetic fields in the vicinity of the working edge of the solar nebula could be amplified to ≈0.2–0.6 G even with a small seed field in the T-Tauri wind.

Note that the above description of magnetic field amplification in the vicinity of the stagnation point depends very much on the validity of treating the entire interaction process as continuous. It is possible also that kinetic effects might have been important in the actual situation, as argued previously for the case of comet–solar wind interactions[17]. But at least the observations at Venus, where these effects could certainly be said to be important in the solar wind interaction process, have indicated that equation (1) is not inappropriate.

In this connection, there is also an important difference between the azimuthally symmetric disk geometry of the solar nebula and those of comets and Venus. Most significantly, in the case of the solar nebula, the draped fields would not be moved away from the flanks by convection. In other words, whereas the stagnation points with enhanced magnetic fields are only localized regions in the vicinity of the hemispherical nose-cones of comets and Venus, for the solar nebula (if axisymmetrically shaped) it could form a belt-like structure extending 360° around the Sun. Without sideways-slippage, all the magnetic flux may tend to accumulate at the front. From this point of view, the maximum value of the draped fields could be increased further beyond the prediction of equation (1). Whether it could reach 2–3 G, as obtained by setting the magnetic pressure equal to a thermal pressure of 10^{-6} bar in a limited region near the contact surface, must be resolved by future quantitative computations. Note that the continuous build-up of the magnetic fields at the front could be balanced only by continuous leakage into the inner region of the solar nebula or reconnection near the stagnation point. Both processes could take place: however, the leakage effect (by interchange instability or ambipolar diffusion) is more interesting as it allows an extensive portion of the solar nebula to be permeated by the draped magnetic fields with a magnitude of ~0.2 G. These fields would eventually be dissipated by magnetic diffusion or, once again, by magnetic reconnection at the equatorial current sheet.

We have extended the magnetic field amplification effect which has been observed in the solar wind–Venus interaction, and which is expected to occur in the solar wind–comet interaction, to the interaction of the dust and gas components of the primordial solar nebula with the T-Tauri wind of the proto-Sun. Using this extrapolation, strong magnetic fields (at least ≥0.1 G) could be generated at the stagnation point of the solar nebula and could even penetrate through the solar nebula to form a thin current sheet at the equatorial plane separating the two regions of opposite magnetic polarity. Whether or not a maximum field strength of 2–3 G could be generated, as inferred from the large permanent magnetization of the Allende meteorite, remains unclear. In any event, we believe that our proposed mechanism is promising compared with the alternatives reviewed by Levy and Sonett[5] and they should be investigated further. We note that the present model may be considered as an important variant of the one involving spreading of the solar magnetic field into the solar nebula (proposal (1))[5]. We expect in fact that a hydromagnetic dynamo field might be generated in the solar nebula (proposal (2))[6] concurrently with the field-draping mechanism proposed here. However, the dynamo mechanism depends critically on the state of turbulence of the solar nebula, whereas the T-Tauri wind interaction scenario is relatively insensitive to the particular assumptions of turbulent velocity and scale-length of the turbulent eddies. Perhaps another point of interest is the azimuthal motion of the ionized matter in the vicinity of the contact point. In an idealized picture, such 'winding' of the draped fields should act to produce a toroidal component of the amplified field: either the draped field could be further enhanced by this process, or it could introduce complicated effects relating to the stability of the system which could be treated only in detailed numerical models. This particular issue, together with the questions of reconnection and leakage of magnetic fields, must await quantitative studies. Finally, in this connection, we note there is uncertainty about the timing between the T-Tauri phase of the proto-Sun and the condensation of the carbonaceous chondrites. However, the importance of the quasi-cometary interaction process as an element in the magnetohydrodynamics of the early solar nebula, as depicted here, is quite independent of these considerations.

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