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Is the Martian Blue Haze Produced by Solar Protons?

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The hypothesis that solar protons produce the Martian blue haze is examined. To reach the atmospheric depth at which the observed haze layer is localized, proton energies in excess of 2 Mev are required. In order to produce sufficient molecular ionization to obscure surface detail in the blue, the proton fluxes must be greater than 10^{11} cm^{-2} sec^{-1} at Mars. So that magnetic deflection of solar protons by the terrestrial magnetic field can explain the clearing of the blue haze which is observed at opposition, the interplanetary magnetic field strength must be less than 10^{-8} gauss. Recent observations argue strongly against these required interplanetary magnetic field strengths and solar proton energies and fluxes. Several further observational tests are suggested, but at the present time it appears that this hypothesis should be rejected.

INTRODUCTION

Urey and Brewer (1957) have suggested that the blue haze that obscures surface detail on Mars at short visual wavelengths is produced by solar protons. These protons, it is postulated, are incident on the upper Martian atmosphere where they produce the molecular ions CO_2^+, CO^+, and N_2^+, all of which have strong band absorption in the required spectral region.[1] The correlation of blue clearing with Martian opposition, an effect apparently not due entirely to observational selection (de Vaucouleurs, 1958; Slipher and Sinton, 1962), is then readily explained by the deflection of solar protons by the terrestrial magnetic field, and the resulting decrease of the proton flux at Mars. This eclipse explanation of the blue clearing was first suggested by Slipher and Wilson (1954).

It is the purpose of the present paper to examine some consequences of this hypothesis. We will first compute the incident energies which the protons must have in order to penetrate to the haze level in the Martian atmosphere, and the fluxes required to make the haze opaque in the blue. Next, the duration of a blue clearing on Mars at favorable opposition will be calculated, on the assumption that the terrestrial magnetic field produces the clearing by deflecting the incident protons. The calculations will be compared with observations of solar proton energies and fluxes, and durations of blue clearings. Finally, some further experimental tests of the hypothesis will be suggested.

REQUIRED PROTON ENERGIES

Estimates of the height of the blue haze have been performed by comparing photographs of Mars taken in long- and short-wavelength light. The height of the haze layer found in this way has ranged from 54 km (Dollfus, 1952) to 200 km (Ross, 1926); the mean altitude in the ultraviolet is 150 km (see e.g., Martz, 1953). However, Sharanov (1950) has noted that the larger apparent diameter of blue images of Mars (Wright's phenomenon) is, in part at least, illusory. The limb darkening of red

[1] Urey and Brewer used "fluorescence" to describe the obscuring effect of these molecular ions, but "absorption" would appear to be a more appropriate term. The albedo of Mars in the blue is much less than in the yellow.

images of Mars will be more pronounced than the limb darkening of blue images; consequently the apparent diameter of the red image will be smaller than the true diameter. That the blue haze is in part a photographic artifact is further borne out by the observation that the apparent diameter of the blue image is relatively independent of exposure time, while the apparent diameter of the red image is a very sensitive function of exposure time (Barabashev and Timoshenko, 1940).

Using a different approach, Kuiper (1952, pp. 421–422) has interpreted the difference between the dynamical oblateness of Mars and the visual and photographic oblateness as due to a haze layer which is higher over the equator than over the poles. On this basis, the equatorial altitude of the haze layer is some 17 km, about one scale height. At the present time it can be concluded that the altitude of the haze layer is probably less than 150 km, and possibly much less.

With 150 km as the maximum height of the blue haze, one finds from Goody's (1957) model Martian atmosphere a pressure at the haze level $> 10^{-2}$ mb. For a mean molecular weight of 28, the mass of the Martian atmosphere above the haze

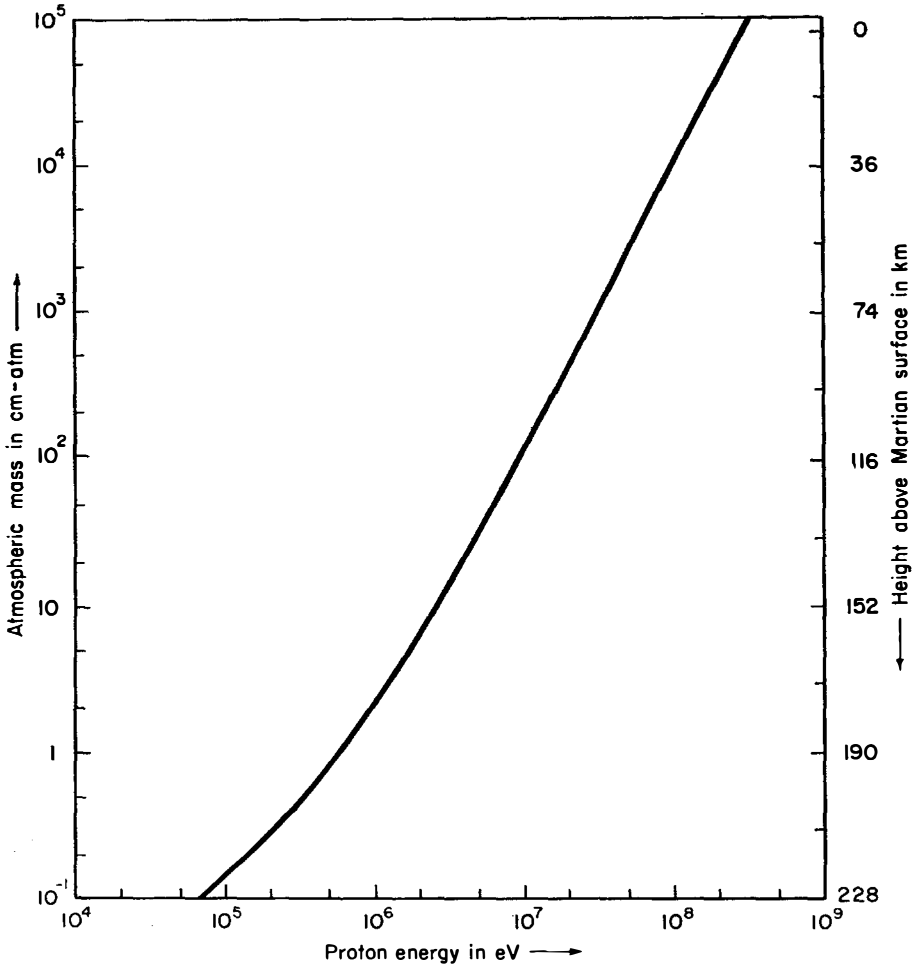

FIG. 1. Range of protons in the Martian atmosphere. The curve gives the atmospheric mass penetrated, and equivalently the altitude above the surface reached, by protons of various initial energies before being thermalized.

is then > 10 cm-atm. A proton with this range in air must have an energy in excess of 2 Mev (see e.g., Bates, 1954, p. 625). Proton energies required to reach other atmospheric depths on Mars are plotted in Fig. 1.

The original suggestion of a solar proton flux (Biermann, 1957) was based on observations of the acceleration of comet tails and required proton energies in the Kev range. Recent theoretical and semiempirical discussion (see e.g., Parker, 1960; Chamberlain, 1961; Brandt, 1962) has been concerned with whether the energies are in this range or whether they are several orders of magnitude less. There is no evidence for a continuous solar proton flux with energies in the Mev range. Even during the period of maximum solar activity, there is no detectable solar proton flux above the atmosphere for 85% of the time (Anderson, 1961). In addition, the solar proton flux varies by factors $\sim 10^7$ between intense solar flares and quiet sun; yet no corresponding or synchronous variation has been noted in the opacity of the Martian blue haze.

Substantial local acceleration of solar protons in the Martian magnetic field is unlikely for two reasons: (1) Mars is believed to have a small or nonexistent fluid core, and therefore probably a very weak surface magnetic field (Urey, 1952; Urey and Brewer, 1957); and (2) if the protons were accelerated in the Martian magnetic field, the blue haze would have a pronounced latitudinal dependence, contrary to observation.

Required Proton Fluxes

For absorption in the blue by molecular ions to be appreciable, optical depths greater than unity must be reached. Assuming a molecular ion cross section of 10^{-17} cm^2, and an atmospheric ion scale height of 34 km, the mean ion number density in the blue haze must be at least 3×10^{10} cm^{-3}. The required flux of incident protons is then

$$F \simeq \alpha N_i^2 H \varphi^{-1}$$

where α is the recombination coefficient, N_i the ion number density, H the scale height, and φ the ion yield per incident proton. Taking $\alpha \simeq 10^{-8}$ cm^3 sec^{-1} (for dissociative recombination), $N_i \simeq 3 \times 10^{10}$ cm^{-3}, $H \simeq 1.7 \times 10^6$ cm, and $\varphi = 3 \times 10^6$ ions per proton (for 100 Mev protons), we obtain $F \simeq 5 \times 10^{12}$ protons cm^{-2} sec^{-1}. Similar fluxes are required for other proton energies in the permissible energy range. Such high values of the flux are entirely inconsistent with present knowledge of the cosmic ray energy spectrum. During a typical year in the solar cycle, the average flux of protons with energies $E > 30$ Mev is $F \simeq 10^3$ protons cm^{-2} sec^{-1} (Anderson and Enemark, 1960); and the contribution by protons in the energy range 1 Mev $\leqslant E \leqslant 30$ Mev is not expected to increase F by more than one order of magnitude.

Furthermore, the high free-electron densities that would be produced (in the absence of extensive attachment) have another unlikely consequence: because of free–free transitions, optical depth unity for radio waves will be reached in the millimeter wavelength region, and microwave emission from Mars at longer wavelengths will arise from the region of the blue haze. Nevertheless, it is observed that the brightness temperature of Mars measured at 3.14 cm is very close to the infrared thermocouple temperatures of the planet (Giordmaine, *et al.*, 1959) rather than to a characteristic ionospheric temperature, as would be expected if such high electron densities existed.

Magnetic Eclipses

The manner in which the terrestrial magnetic field eclipses the solar proton flux is of some interest. The maximum distance from the center of Earth at which the terrestrial magnetic field is still effective in deflecting solar protons is given by the distance at which the interplanetary and terrestrial magnetic fields are of the same order. At greater distances particle trajectories will be determined by the interplanetary field. Taking the quiet sun interplanetary magnetic field strength as 1×10^{-4} gauss $\geqslant B_i \geqslant 1 \times 10^{-5}$ gauss (Coleman, Davis, and Sonett, 1960; Coleman, Sonett, and Davis, 1961; COSPAR Information Bulletin, 1961), and using a dipole approximation to Earth's field, we find that $B_i = B_{\oplus}$ at $35 \geqslant r \geqslant 20$ Earth radii. Direct measurements of the geomagnetic cutoff have been made from Pioneer I (Sonett, Judge, Sims, and Kelso, 1960), and give $r = 14$ Earth radii. However, the flight was made above the day hemisphere of Earth, and some compression of the terrestrial magnetic field by the interplanetary medium can be expected. We will be generous with the blue haze mechanism under consideration, and adopt $35 \geqslant r \geqslant 20$ Earth radii, as seen from above the antisolar point. Very energetic particles will not be deflected appreciably until they pass considerably closer to Earth.

Consequently the terrestrial magnetic field begins effectively to deflect solar protons away from the direction of Mars at 20 to 35 Earth radii, or less. There will be some focusing of particles towards Mars, and into the shadow region, but, again to be generous, we assume that this effect will be negligible compared with the deflection away from Mars. Accordingly we represent the effect of the terrestrial magnetic field on the incident solar protons by a geometrical shadow cone extending from Earth to Mars, with a base at Earth of area πr^2, where r lies between 20 and 35 Earth radii.

The angular diameter of the proton-eclipsing cross section of the terrestrial magnetic field as seen from Mars at favorable opposition (Earth–Mars distance 6×10^7 km) then lies between 0.24° and 0.42°. The angular diameter of the sun as seen from Mars at the same time is about 0.36°. Therefore the possibility exists that some eclipses will be total or near-total. At unfavorable oppositions, and especially when Mars is at high heliocentric latitudes, the eclipse will not be total. The relative angular velocity of Earth and Mars is 0.46° per day. Consequently the time interval between first and fourth contacts for a central eclipse will be between 1.3 and 1.7 days in the most favorable case, and less for nontotal eclipses and unfavorable oppositions.

Most reported durations of opposition blue clearings lie in the range between 1 and 30 days, although there is a tendency for blue clearings at favorable oppositions to last nearer 30 days than 1. The clearing of 1954 observed by Slipher (cited by Goody, 1957) extended some 60 days. From examination of Lowell Observatory photographs taken by E. C. Slipher, de Vaucouleurs (private communication, 1961) has concluded that the blue haze reaches $1/e$ its ordinary opacity some 20 or 30 days from the onset of blue clearing. Thus the observed duration of blue clearing greatly exceeds the computed duration.

To explain the blue clearing as a shadow effect accordingly implies that the effective proton-eclipsing cross section of Earth has a radius of some 500 earth radii. For the terrestrial dipole field to dominate the interplanetary field out to this distance, the values of the interplanetary magnetic field strength must be less than 10^{-8} gauss. This value is much less than probe results for the interplanetary field indicate and is even smaller than the interstellar field in the galactic spiral arms. The observed distance of the geomagnetic cutoff is also entirely inconsistent with the requirements of this model.

Other Consequences and Conclusions

The solar-proton hypothesis of the origin of the blue haze has several further consequences, many of which can be tested with existing and forthcoming observations:

(1) There must be a flux of protons with energies in excess of 1 Mev and fluxes $> 10^{11}$ cm^{-2} sec^{-1} on almost rectilinear trajectories from the sun to Mars.

(2) The Martian magnetic field must be so small that the particles are not deflected away, even at low areocentric latitudes.

(3) Molecular ion recombination in the haze layer should give an intense twilight airglow which should be easily visible from a flyby probe. For example,

$$N_2^+ + e \rightarrow N^* + N^{**}$$
$$N^* \rightarrow N + h\nu$$

should give a strong line near 5199 A.

(4) There should be a correlation of the degree of blue clearing with the relative heliocentric latitudes of Mars and Earth.

(5) Blue clearings which occur away from opposition should disappear shortly after the appearance of a solar proton event.

The preceding five observations or correlations will provide a final test of the hypothesis that the Martian blue haze is produced by solar protons. At the present time this hypothesis appears untenable, because it requires unrealistically large values of the solar proton flux, and unrealistically small values of the interplanetary magnetic field strength.

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