FURTHER OBSERVATIONS OF THE ZODIACAL LIGHT FROM A HIGH ALTITUDE STATION AND INVESTIGATION OF THE INTERPLANETARY PLASMA

1. Introductory Survey and Photoelectric Measurements of Brightness


(Received 1963 September 13)*

Summary

Observational knowledge of the electron density in interplanetary space is briefly reviewed, and the methods used during an expedition to Chacaltaya, Bolivia, outlined. Results of scans of the zodiacal light with a photoelectric photometer made in the course of the investigation are first presented, and a new method used to separate the zodiacal light from the night sky background. The isophotes thus obtained are corrected for the effect of scattering in the Earth’s atmosphere to give the true isophotes.

1. Introduction.—Knowledge of the distribution of free electrons in the solar corona and in interplanetary space is still very meagre. Whilst we may say that radio observations have shown the presence of free electrons at distances from the Sun of up to 100R⊙, and experiments with probes have demonstrated the existence of a high speed particle stream from the Sun of density in the region of 10 cm⁻³ at a distance of 1 A.U., we cannot yet say that we have a complete knowledge of electron densities beyond about 4R⊙ from the solar limb, even in the vicinity of the equatorial and ecliptic planes. This is an important gap in our knowledge for we cannot hope to understand the nature of the Sun’s extended atmosphere until we know its density out to distances of about 1 A.U. The purpose of these papers is to present new optical data concerning the zodiacal light and night sky which are used to impose limits on the maximum possible electron density at a distance of 1 A.U. from the Sun; these limits are lower than values so far obtained by such methods. The data on which these papers are based were obtained during an Oxford–Cambridge expedition to the mountain site of Chacaltaya in Bolivia during the period May to August, 1961.

2. Previous investigations of electron density.—For our knowledge of the electron density in interplanetary space we are still partly dependent upon studies of the polarization and spectrum of the zodiacal light. Information also comes from investigations of the occultation of radio sources by the outer solar corona and studies of the accelerations of individual features in comet tails. The evidence from upper ionosphere work serves as a useful pointer to conditions

* Received in original form 1963 May 30
in interplanetary space. Finally, direct measurements have been made during the last two years by American and Russian investigators using space probes.

The papers of Blackwell & Ingham (1, 2, 3) and Ingham (4) reviewed very briefly investigations of interplanetary electrons and dust up to 1958. Since then there have been reviews of the interplanetary gas by Rossi (5) and of the interplanetary material by Parkin & Hunter (6) and Manring (7).

One of the difficulties in 1958 was the reconciliation of results from comet studies with those given by other methods. Biermann (8, 9) and Parker (10) had attributed the accelerations already mentioned to interaction between the cometary material and a particle stream from the Sun, and had deduced a value for the particle density of between $10^3$ and $10^5$ cm$^{-3}$. This seemed unreasonably high, for not only did it exceed the upper limit of 120 cm$^{-3}$ for the electron density at 1 A.U. given by Blackwell and Ingham (2), but a corpuscular beam of density $10^5$ cm$^{-3}$, if of thickness 0.5 A.U., would be visible by electron scattering with a brightness equal to about 50 times that of the zodiacal light. This difficulty has recently been resolved by Hoyle & Harwit (11) and Harwit & Hoyle (12) who pointed out that much smaller densities than those given by Biermann and Parker would be required to explain the observations if it were supposed that a transverse magnetic field exists in the solar stream. It now seems that cometary data cannot give quantitative information about the density of corpuscular streams, although they undoubtedly indicate the existence of such streams and possibly reveal their structure.

The experiments with the Explorer X (13), Lunik II (14, 15) and Mariner II space probes have greatly increased our knowledge of plasma densities. The technique involves the collection of high-speed charged particles, and all the experiments have shown the existence of a proton flux from the quiet Sun; Explorer X showed a flux of about $4 \times 10^8$ proton cm$^{-2}$ sec$^{-1}$ with an energy of 500 eV indicating a plasma density of between 6 and 20 protons cm$^{-3}$, while Lunik II showed a flux between $2 \times 10^8$ and $10^9$ protons cm$^{-2}$ sec$^{-1}$.

Pope (16) has measured electron densities in the exosphere using the phenomenon of "nose whistlers" and obtained values between 5 and 20 cm$^{-3}$ at heights of between $4R_E$ and $6R_E$.

Observations of the zodiacal light have been used in two ways to give information about electron densities. Fundamentally, the problem is to separate the light into contributions arising from scattering of sunlight by interplanetary dust and scattering by interplanetary electrons. Behr & Siedentopf (17) initially made this separation by making use of the total polarization of the light, which is in the region of 35 per cent, and assuming that the light scattered by interplanetary dust has zero polarization; this method gives an upper limit of 600 cm$^{-3}$ to the density at 1 A.U. In a development of this method Giese & Siedentopf (18) have attempted to evaluate a maximum likely value for the polarization of the dust component. They have been unable to attribute all of the observed polarization to dust scattering, and deduce from this that the electron density cannot be less than 300 cm$^{-3}$. This result is not supported by the work of Fesenkov (19) who has measured the polarization of the light scattered by the dust of the upper atmosphere of the Earth. He has obtained the value of 27 per cent, which suggests that dust scattering may also be capable of accounting for much of the polarization of the zodiacal light. From this measurement he has calculated the polarization of the zodiacal light assuming that
the scattering properties of interplanetary dust are similar to those of atmospheric dust.

During their 1958 expedition to Chacaltaya, Blackwell and Ingham photographed the spectrum of the zodiacal light at a high dispersion (38 A/mm) and compared the depths of selected Fraunhofer lines in the spectra of the zodiacal light and of the Sun. The result was that the depths were not significantly different, and the deduction from this was that not more than 10 per cent of the zodiacal light spectrum consists of purely continuous component; hence the electron density at 1 A.U. from the Sun cannot be greater than 120 cm\(^{-3}\). This result has recently been criticized by Schmidt & Elsasser (20) who have suggested that the observations are compatible with a maximum electron density of 400 cm\(^{-3}\). The maximum permissible electron density obtained by this method depends upon an analysis of the errors and uncertainties in the observations, and we here remark only that we do not agree with the treatment by Schmidt and Elsasser. In particular, if we may isolate one of their points, we do not believe that physically impossible observations for the line depth should be omitted from the analysis; this is analogous to omitting negative values of stellar parallax in discussing the mean value of some parallax observations of a star. Such values exist only because of natural errors and should be retained. However, it would be out of place to consider the criticisms further here.

If subsequent work should confirm that the density is less than 120 cm\(^{-3}\), then most of the zodiacal light is due to dust scattering, and we are faced with the problem, so far unsolved, of accounting for its high polarization.

3. Desirability of optical methods.—It might be argued that now a direct method using an interplanetary probe is being used no other method is needed. But, whilst the sensitivity of the direct method is great, the method so far depends upon the interplanetary ions moving at considerable speed. Although, according to Parker's theory of the solar wind (10, 21, 22, 23) all of the ions must be moving at high speed, so that the direct method gives complete information about ion densities, we suggest that it is desirable to seek confirmation of the results of the direct method by independent optical means if possible; this is particularly so because Chamberlain's theory (24, 25) indicates much lower velocities. We do not believe that the results of the interplanetary probe experiments demonstrate conclusively that Parker's theory is correct. The optical method has two advantages; one is that it is independent of the ion speed and so will detect a stationary plasma if it exists, the other is that it averages the electron density over a path length of about 1 A.U.

4. The purpose of the observations.—The observations were made during the summer of 1961 by a joint Oxford–Cambridge expedition working at the high altitude laboratory on Mount Chacaltaya, Bolivia. A description of the site and its advantages has already been published (1).

The prime aim of the 1961 expedition was to check the upper limit of 120 cm\(^{-3}\) already set upon the electron density by the 1958 expedition, and if possible to improve the accuracy of those observations so that either a still smaller upper limit could be set, or else an actual measurement of density made. The new results are of particular interest in view of the 1958 criticism of the results by Schmidt and Elsasser.

During 1961 two methods were used. The first was to compare selected Fraunhofer lines in the true zodiacal light spectrum with their counterparts in
the spectrum of the Sun, using a photoelectric technique. The advantages of this method over the photographic technique used in 1958 are two-fold. One is in speed, for it proved possible by photoelectric means to make a significant measurement on the zodiacal light in four minutes, whereas to obtain a photograph of the spectrum an exposure time of 7 hours, equivalent to one week's observing, was required. The other is the increased accuracy associated with photoelectric working. On both counts there is an increase in ultimate accuracy, for the photographic method depends upon the reduction of one spectrum only, whereas the photoelectric method enables the mean of many results to be taken.

The second method was to measure, also by a photoelectric technique, the polarization of the zodiacal light, and of the night sky in regions away from the ecliptic and, in particular, near to the ecliptic pole. When working in the plane of the ecliptic we are seeking to distinguish the faint light scattered by electrons against the much stronger light scattered by interplanetary dust. An investigation far from the ecliptic does not suffer from this difficulty, for whilst the dust component is closely associated with the ecliptic, an electron component need not be related to the ecliptic at all (26) so that the chances of its detection in these regions are correspondingly greater.

5. The presentation of the results of the expedition.—In order to determine the electron density from the spectrophotometry and the measurements of polarization we need to know in addition the brightness of the zodiacal light and of the night sky. The measurements of brightness are only incidental to the main investigation of the electron density, but since photometric studies of the zodiacal light from high altitudes are not numerous, and since our observations are peculiarly suited to the determination of isophotes, we devote the rest of this first paper to them.

The spectrophotometric investigation is described in Paper II of this series, and the study of polarization in Paper III; both of these papers make use of the measurements of brightness described here.

6. The photometry of the zodiacal light

6.1. The apparatus.—A photometric investigation of the zodiacal light was made on 18 nights during the expedition. As explained above the prime purpose of this was to obtain the ratio of the zodiacal light brightness to that of the background night sky, so that the spectrophotometric measurements on the zodiacal light could be corrected for the sky background.

A diagram of the optical arrangement of the zodiacal light photometer is shown in Fig. 1. The objective is a simple lens of diameter 7.5 cm and 16.5 cm focal length, which is imaged by a Fabry lens on the cathode of an E.M.I. trialkali photomultiplier (Type No. 9558). Scanning apertures of diameter 0.79 degrees and 2.56 degrees were available with various colour filters. The photometer could be elevated to any required altitude, and was rotated about a vertical axis by an electric motor at the rate of 1 turn in about 90 seconds. The output of the photomultiplier was amplified with a D.C. amplifier and displayed on a pen recorder, using a time constant of about 0.5 seconds. A screen made of several thicknesses of white blotting paper was illuminated by a standard lamp to give an absolute calibration.

Scans were made at constant altitude over a range of 250° in azimuth centred about the ecliptic, using Chance OB10 (blue) and OY1 (red) filters. A third
filter, a combination of Chance OB10 and OY8 filters, isolated a narrow region of the spectrum centred at a wavelength close to Hβ. This filter was used because the Hβ line was investigated spectroscopically; its transmission is shown in Fig. 2. Figure 3 shows a reproduction of a typical scan of the zodiacal light made with this apparatus and the Hβ filter at a zenith distance of 81° and intersecting the ecliptic at an elongation of 28°. On all occasions except for a brief period during one evening the sky near the horizon was free from cloud and seemed to have the usual extreme transparency (1).

![Optical arrangement of the zodiacal light photometer.](image)

**Fig. 1.** Optical arrangement of the zodiacal light photometer.

![Transmission of the Hβ filter.](image)

**Fig. 2.** Transmission of the Hβ filter.

6.2. The apparent zodiacal light and the night sky background.—We distinguish in this series of papers between the true zodiacal light, which is the zodiacal light as seen from outside the Earth’s atmosphere and corrected for the star background, and the apparent zodiacal light, which is the true zodiacal light altered
by atmospheric absorption and scattering. Observations of the total brightness have, of course, initially to be corrected for the brightness of the night sky to give the apparent zodiacal light.

We have reduced the zodiacal light scans using the method of Roach et al. (27) but only to give the brightness of the apparent zodiacal light along the ecliptic. Figure 4 shows the ratio of this brightness to the total brightness (i.e. including night sky) at a zenith distance of 81° and covering the range of elongation 26° < ε < 38°. This diagram contains every measurement of this ratio obtained with the Hβ filter, and it demonstrates that, at a favourable site, we may observe zodiacal light without excessive contamination by night sky background, by using a suitable filter at small elongations. The ratio is smaller for the OY1 (red) filter because of the presence of the night sky emission lines at 6300 and 6363 A, even though the zodiacal light itself is brighter because of the increased atmospheric transmission at longer wavelengths.

Fig. 3.—Scan of the zodiacal light at a zenith distance of 81° and an elongation of 28°; the trace has been selected as one free of disturbance by bright stars along the line of scan.

6.3. Determination of the isophotes of the true zodiacal light.—There are two reasons why these are very difficult to determine. The principal one is the absence of criteria which can be used to separate the apparent zodiacal light from its mixture with the night sky background at large ecliptic latitudes, where the two are probably comparable. It will be clear that a small error in the brightness of the sky background here will lead to a large error in the zodiacal light intensity and a serious deformation of the isophotes.

The second difficulty, which was first pointed out by Fesenkov (28), is that some of the light observed at large ecliptic latitudes is light that has been scattered by the Earth's atmosphere from the main cone of the zodiacal light. The correction for this is small at Chacaltaya because of the unusually great transparency of the atmosphere there at large zenith distances.

We have effected the principal separation of the apparent zodiacal light from the total brightness in two stages. First we use Roach's method to make the
separation on the ecliptic alone. In a second step, to make the separation in regions of the zodiacal light away from the ecliptic, we make use of measurements of the polarization. To explain this second stage we begin by anticipating the result of Paper II, that the electron density at 1 A.U. from the Sun is less than 36 cm$^{-3}$. This means that no more than 3 per cent of the zodiacal light near the ecliptic is due to electron scattering. The degree of polarization of the light scattered by any reasonable distribution of free electrons alone in interplanetary space will be in the region of 50 per cent. As this is not far from the 35 per cent polarization of the zodiacal light measured on the ecliptic (97 per cent of which

![Fig. 4.](image)

**Fig. 4.—The ratio of the brightness of the apparent zodiacal light on the ecliptic to the total brightness, as a function of elongation, and using the Hβ filter.**

light is due to dust scattering), the polarization of the sum of the dust and electron components cannot differ greatly from that of the dust component alone for any acceptable proportion of electron component. We now assume that to the accuracy we require, the polarization of the dust component depends on the angular distance of the point of observation from the Sun.

At a position away from the ecliptic at distance $r$ from the Sun, let the brightness of the apparent zodiacal light be $B_z$ and that of the night sky background be $B_s$. Further, let the observed total polarization be $P_{z+s}$, the polarization of the apparent zodiacal light be $P_z$ (assumed equal to the polarization measured on the ecliptic at elongation $\epsilon = r$), and that of the sky background be $P_s$.

Then

$$B_{z+s} \times P_{z+s} = B_z P_z + B_s P_s.$$

Assume now that $P_s = 0$, obtaining,

$$\frac{B_z}{B_{z+s}} = \frac{P_{z+s}}{P_z}.$$
This gives $B_z$, knowing $B_{z+8}$. Previous determinations of $B_z$ at high ecliptic latitudes have been uncertain by a factor of at least $\times 3$. However, in the above method, even if $P_z$ is in error at any one point by 20 per cent of its value (e.g. if it assumed to be 28 per cent instead of 35 per cent) the error in $B_z$ is only 20 per cent.

In Paper III we describe measurements made at Chacaltaya of the polarization of the zodiacal light and the night sky background over a range of ecliptic latitudes. These measurements have been used in the way described above to separate the apparent zodiacal light from the night sky background at larger ecliptic latitudes, and hence to obtain isophotes of the apparent zodiacal light. These isophotes have been further corrected for the presence of scattered light, using the results of computations made by Wolstencroft (29), to give isophotes of the true zodiacal light. The results are given in Fig. 5, which shows also an isophote of the solar corona at about 6° from the Sun as observed (30) at a total solar eclipse near sunspot minimum. The whole width of the zodiacal light to half intensity is about 25° over a range of elongations between 30° and 40°.

![Isophotes of the true zodiacal light](image)

**Fig. 5.—Isophotes of the true zodiacal light. The innermost isophote is one for the solar corona at about 6° from the Sun, with the solar equator arbitrarily orientated along the ecliptic.**

We wish to emphasize that this is only a preliminary trial of a new method and that the determination of the isophotes was not the principal object of the expedition. More reliable results could be obtained by making a more detailed
investigation of the polarization at high ecliptic latitudes than was possible on this expedition. As we have pointed out, the problem is one of great difficulty and probably the only truly satisfactory method of obtaining these isophotes is to make observations from above the emitting layers of the Earth’s atmosphere.

6.4. Absolute intensity of the zodiacal light.—As in this investigation we are interested almost entirely in the ratio of the brightness of the apparent zodiacal light to that of the night sky background, we have not paid particular attention to the determination of the atmospheric extinction. We therefore present only the average of three absolute measurements of brightness, viz. those of June 14, July 5 and 6, when observations of the extinction were made which agreed well with those made during 1958 expedition. At elongation $\epsilon = 40^\circ$ this brightness was $3.8 \times 10^{-13}B_\odot$. Previous measurements of brightness have been summarized by Blackwell and Ingham (1) and yield a mean brightness at this elongation of $3.86 \times 10^{-13}B_\odot$; the above determination agrees with previous results, and we do not consider that the available data show any systematic variation with time over a period of ten years.

(DWB and DWD)
The Observatories, 
Madingley Road, 
Cambridge.


(DEB)
Department of Astrophysics, 
South Parks Road, 
Oxford.

(RDW)
Kitt Peak National Observatory, 
950 North Cherry Avenue, 
Tucson, 
Arizona, 
U.S.A.

1963 September.

References

(9) L. Biermann, Observatory, 77, 109, 1957.