OBSERVATIONS OF THE ZODIACAL LIGHT FROM A VERY HIGH ALTITUDE STATION

III. THE DISTURBED ZODIACAL LIGHT AND CORPUSCULAR RADIATION

D. E. Blackwell and M. F. Ingham

(Received 1960 October 6)

Summary

Photometric observations of the zodiacal light made at Chacaltaya in the Bolivian Andes during 1958 show that there are changes in brightness which are correlated with geomagnetic activity. The changes in the zodiacal light and the surrounding sky during the intense magnetic storm of 1958 July 8–9 are described. The increase in sky brightness that was then observed is tentatively ascribed to scattering by free electrons in a corpuscular stream, the electron density in the stream being about 300 cm$^{-3}$. There was also a corresponding increase in zodiacal light brightness; the hypothesis that this may be attributed to fluorescence of the interplanetary dust on impact with the protons of this corpuscular stream is examined, but found to be inadequate.

Introduction.—Whilst at Chacaltaya the 1958 Cambridge Observatories expedition* made a special study of the variation with time of the brightness of the zodiacal light and the surrounding night sky. Previous studies of this problem by other observers had given conflicting data and we hoped that the exceptional atmospheric conditions at Chacaltaya would enable us to decide whether or not the zodiacal light itself varies in brightness or position. Whilst this was not the primary problem, we also wished to examine the possibility of detecting corpuscular radiation directly, during its passage between the Sun and Earth, through the scattering of sunlight by free electrons in the corpuscular stream. The time of the expedition was particularly favourable for studies of this kind, for the observations were made at the peak of the solar cycle during a period when the solar activity was exceptionally great.

Previous observations of changes in the brightness of the zodiacal light.—There have been many reports of variations in the brightness of the zodiacal light. We list some of these below, but at the same time we emphasize most strongly that studies of possible variations in the zodiacal light can be made only with great difficulty and any results should be treated with extreme caution. Worthwhile data can scarcely be obtained except from good photographic or photoelectric photometry carried out under excellent meteorological conditions in the tropics, and for this reason we reject almost all of the available visual observations, even

* The circumstances of the Cambridge Observatories expedition to Chacaltaya and the observations of the brightness, polarization and position of the zodiacal light made there are described in Paper I of this series.
though they have been made with the greatest care. The principal changes that have been reported are as follows.

(i) **Short period fluctuations.**—Reports of changes occurring during one evening within a time interval of a few minutes are common. The best known study of this kind is that of Jones (1) made between 1853 April 2 and 1855 April 21, during a voyage on the Pacific Ocean chiefly between latitudes +20° and +40°. Jones’s observations were made visually whilst he was on board ship, and he recorded the brightness and position of the zodiacal light together with changes in its brightness which he called “pulsations”. Hulburt (2) has drawn attention to the correlation that exists between these times of zodiacal light variability and the times of magnetic activity as observed at Greenwich. Jones himself was unaware of any such relationship, and it is difficult to escape the conclusion that the phenomena described by him did actually occur*. There are other reports in the literature—see, for example, Hulburt (2)—of changes in the zodiacal light during periods of auroral activity, but we postpone until later the question of whether the observer is deceived by the presence of aurorae into thinking that the zodiacal light has changed.

(ii) **Occasional enhancements of the zodiacal light during one whole night.**—Visual observations of this kind are not uncommon (2), and we refer here only to the unusually bright zodiacal light of 1896 March 4 (3), which occurred during a period of auroral activity. Apparent changes of brightness from night to night occur in most detailed lists of photometric observations—see, for example, Roach (4) and Huruhata (5)—although an opinion is rarely expressed about the reality of these apparent changes.

(iii) **An annual variation.**—An annual variation of brightness over a range of two to one has been observed photoelectrically by Elvey and Roach (6). Thom (7) has assembled many visual observations from a variety of sources and has found a similar variation.

(iv) **Long period variations.**—Huruhata (5) has made photoelectric observations over a period of four years, finding an irregular variation from year to year amounting at most to a factor of seven. Thom (7), using the previously mentioned visual data, also finds a variation and some correlation with solar activity. Table IV of Paper I, which lists absolute brightness values obtained by various observers during the period 1952-8, using non-visual techniques, apparently supports this idea that there is a variation from year to year.

All of this evidence is contradicted by Regener (8) who cannot find any significant variation during fourteen months continuous observation over the period 1953–4. It is perhaps significant, however, that his observations were made during a period of very low solar activity. A daily record of the appearance of the zodiacal light at the Harvard College Observatory (latitude 42°N) over the period 1876–1890, has been analysed by Searle (9) who states that the variations which seem to have occurred cannot be established with certainty, and any support for a correlation between the variation and the occurrence of aurorae is certainly very feeble. Barbier (10) also, working photoelectrically at Haute-Provence (latitude

*He noted in his diary for 1854 January 30, “There can be no doubt that there are pulsations in the zodiacal light. I noticed them last evening; but, it being Sunday, made no particular record of them.”
+44°), finds no evidence for a variation of zodiacal light brightness. He worked during the periods 1951–2 and 1952–3 when solar activity was low.

We conclude that it is not possible to deduce from the existing data whether or not the zodiacal light is of constant brightness.

The Chacaltaya observations.—The requirements for a site suitable for an investigation of possible variations of the zodiacal light are very stringent. Evidently the site must be near the geographical equator so that the varying inclination of the ecliptic to the horizon does not lead to systematic errors, and it must also be at a high altitude so that observations may be made close to the horizon, and have an excellent climate in which the extinction is low and varies little from night to night. In addition, it must be near the geomagnetic equator so that there is as little disturbance as possible from aurorae. Chacaltaya satisfies all of these requirements. In particular, it is at a low geomagnetic latitude (−3°) and so is especially suitable for the attempted observation of corpuscular radiation mentioned at the beginning of this paper.

The method of observing the zodiacal light and the results have already been described in Paper I. In this section we attempt to ascertain whether or not the observed variation in these data from day to day can be regarded as real.

Correlation between brightness measurements at λ4470Å and λ6200Å.—The measurements of brightness in these two spectral regions have been made almost completely independently, and we may therefore test the reliability of these measurements by examining the correlation between them. To do this we have,

**Fig. 1.—Correlation between mean surface brightness of the zodiacal light at the two wavelengths 4500Å and 6200Å.**

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System
for each photograph, averaged over all elongations the deviation from the mean brightness. In Fig. 1 we plot one set of measurements against the other and obtain a reasonably good correlation with a slope of unity, showing that the same relative change of brightness occurs in the two spectral regions.

Further, supposing that a perfect correlation may be expected to exist between the two quantities, the diagram shows that the probable error of such brightness measurements, averaged over one plate, is about 8 per cent.

Correlation between zodiacal light brightness and solar activity.—As it now seems likely that the observed variations of brightness are real, we attempt to correlate them with solar activity, as indicated by the magnetic index $K_p$. We have been particularly fortunate during the expedition to have observed the zodiacal light before, during and after the magnetic storm following an important solar flare. The flare occurred on July 7 at 00h 39m U.T. and was recorded at Mitaka and Hawaii Observatories (11) as of importance $3^+$. The intense magnetic storm which followed it on July 8-9 was one of the most important during the three year period 1957—9, the value of the planetary magnetic index $K_p$ (11) remaining at 9 for 15 hours.

In Figs. 2 and 3 we reproduce the plot of surface brightness against elongation for the two colours, which has already been given in Paper I, and show the points appropriate to days when the magnetic index $K_p$ was greater than 4 (i.e. exceptionally high) at the time of observation; evidently there is a fair correlation between magnetic index and brightness in the two colours.

**Fig. 2.—Surface brightness of zodiacal light at wavelength 6200Å showing values appropriate to active days.**
Fig. 3.—Surface brightness of zodiacal light at wavelength 4500Å showing values appropriate to active days.

Fig. 4.—Change of average brightness of zodiacal light as a function of magnetic index.
To investigate this relation further we have formed for each day the deviation of brightness from the mean averaged over elongation and over the two colours. In Fig. 4 these deviations are plotted as a function of magnetic index for the time of observation, showing a remarkably good correlation, the total change in brightness when the magnetic index changes between 0 and 9 being about 40 per cent. The correlation is not substantially altered when a phase difference of up to one day is introduced. These results apparently justify the suspicion that has existed for more than a century, that the zodiacal light itself does change during a time of auroral activity. We emphasize that this observed change in zodiacal light brightness is quite distinct from a change in general sky brightness which may or may not be due to a localized aurora*. However, no rapid changes of the kind described by Jones were observed, either visually or photographically, and we are inclined to doubt whether these changes are associated with the zodiacal light itself, remembering that Jones often observed at rather high geomagnetic latitudes.

We have examined other published photometric data for the effect, but have found that the data are too scanty and the range of magnetic index too small to show a good correlation.

We have examined other published photometric data for the effect, but have found that the data are too scanty and the range of magnetic index too small to show a good correlation.

**Fig. 5.—Relation between brightness of zodiacal light at $\epsilon=40^\circ$ and date of observation; a correction has been made for magnetic activity using the data of Fig. 4.**

*The difficulty of distinguishing between a change in zodiacal light brightness and a change in sky brightness is further discussed on p. 150.
The graph is a weighted mean of observations made in the blue and red regions. All of the photographs were taken at approximately the same time in the evening and reduced in the same way; a correction was made for extinction, using for this purpose observations of stars made with a photoelectric telescope. The graph shows no evidence for an annual variation of brightness such as has been observed by Elvey and Roach (6).

The position of the symmetry axis of the disturbed zodiacal light.—Six representative points on the symmetry axis for the dates July 8, 9 (when the magnetic index was greatest and the zodiacal light most disturbed) are shown plotted in Fig. 6, together with data from all other dates; the points for the two active days are averages for red and blue light. The scatter of all the points indicates the probable error of the data obtained on inactive days, and we conclude that the zodiacal light was not significantly displaced from its normal position on these two occasions.

![Diagram of the symmetry axis of the zodiacal light](image)

Fig. 6.—Symmetry axis of quiet zodiacal light and points obtained on active days.

Although we do not give isophotes for the zodiacal light, our scans show that there was not a significant change in the shape of these isophotes on the active days, i.e. the zodiacal light cone brightened as a whole.

The brightness of the night sky.—We quote here the night sky brightness at an altitude of 15° above the horizon, both on the ecliptic and at about 45° on each side of the ecliptic. The greatest change of brightness during the magnetic storm of July 8–9 was observed north of the ecliptic. To illustrate this we plot in Fig. 7 as a function of date the relative sky brightness measured in the red and blue regions, together with the planetary magnetic index $K_p$. There is evidently a close correlation between the brightness data for the two wavelength regions, and also a correlation between brightness and magnetic index; the increase
in brightness at the time of the storm on July 8-9 is particularly striking. The background sky brightness on the ecliptic, obtained by interpolation between the background at the sides of the zodiacal light, also changed, but it shows a much weaker correlation with magnetic index, the sharp rise on July 7 being scarcely discernible. The same is true of the brightness of the sky south of the ecliptic.

The following diagram, Fig. 8, summarizes these observations of the effect of a solar flare on the zodiacal light and the neighbouring night sky. The diagram shows typical scans across the zodiacal light made under quiet conditions and soon after a solar flare; the level of the night sky background is also shown. The brightness of the zodiacal light itself increased but its position remained unchanged; these effects are superimposed on a changed night sky background. It is clear from this diagram that it is difficult to obtain the true brightness of the zodiacal light under disturbed conditions because of the uncertainty of the interpolation of the sky background between measures made north and south of the ecliptic. In our work we have made a linear interpolation. Because of this difficulty all observations of this nature should be treated with great caution. The most reliable data are those which refer to small elongations where the ratio of zodiacal light to the sky background is a maximum.

The colour of the increment of light from the northern night sky.—This is difficult to establish with precision. Using the data of Fig. 7 and allowing for extinction,
Fig. 8.—Effect of a solar flare on the zodiacal light and night sky brightness. The diagram shows representative scans across the zodiacal light before, and soon after, a flare.

Fig. 9.—Position of solar flare on July 7 in relation to the evening sky.
we find that the extra light which comes from the northern night sky during enhanced magnetic activity has approximately the same colour as the solar disk. The actual ratio observed is

\[
\text{Brightness of increment of night sky at } \lambda 0.62 \mu \text{m} / \text{Brightness of Sun at } \lambda 0.62 \mu \text{m} \\
\text{Brightness of increment of night sky at } \lambda 0.45 \mu \text{m} / \text{Brightness of Sun at } \lambda 0.45 \mu \text{m} = 1.15 \pm 0.20.
\]

The large probable error is a measure of the difficulty of this observation.

Interpretation of the observed effects of the solar flare.—We begin by describing the circumstances of the flare of July 7. The flare occurred at the following position on the solar disk — N24°, W09°. Examination of Fig. 9 shows that a jet of corpuscular radiation emitted from the region of this flare in a direction normal to the solar surface would be directed away from the Earth, and carried away further by the solar rotation. Nevertheless, the occurrence of an intense geomagnetic storm shows that the Earth must have passed through at least the outer parts of the stream during July 8—9. The corpuscular stream was also responsible for marked perturbations in the motion of the Satellite 1958S1 (12). The increased brightness of the northern sky observed in the period June 9 onwards (see Fig. 7) is probably also due to the same active group, although no important flares were recorded during this period.

The observed increase in general sky brightness may be attributed either to an aurora or to the scattering of sunlight from the free electrons contained in a corpuscular stream. We incline to the second explanation for the following three reasons. First, the increase in sky brightness is observed chiefly in the part of the sky which is north of the ecliptic and this is compatible with scattering from a corpuscular stream emitted from an active region on the northern hemisphere of the Sun. Second, the colour of the additional sky light is close to that of the Sun, whereas aurorae often appear red or green. Third, aurorae occur only very rarely at the low geomagnetic latitude of 3°S. Alternatively, it might be argued that if the extra sky brightness is really due to scattering in interplanetary space, the increase should have started soon after the flare itself—whereas the brightness increased with the magnetic activity. This argument is not correct. According to Fig. 9, the corpuscular stream was initially directed away from the Earth, and the diagram of Fig. 10, which shows the corpuscular stream projected on to the plane of the ecliptic, shows that the effect need not be expected until at least one day after the flare.

Supposing that the effect is really due to scattering by corpuscular emission, we may calculate from the increase in brightness the order of magnitude of the electron density in such a temporary corpuscular stream, which should be distinguished from a more or less permanent interplanetary gas. If, on the other hand, the effect is not wholly due to electron scattering, the density obtained represents an upper limit. Taking the data already given, and assuming that we are looking through a total path length of about 0.5 A.U. in the corpuscular stream, the density would be about 300 electrons cm\(^{-3}\), assuming that it is independent of distance from the Sun. Such a value is not incompatible with those already suggested on other grounds. For example, Biermann (13) has suggested that the disruption of comet tails is caused by solar corpuscular radiation, and he supposes a density between \(10^8\) and \(10^9\) atoms cm\(^{-3}\). Chamberlain (14), using the observed intensity of H\(\alpha\) in aurorae, has proposed the value of 1 atom cm\(^{-3}\). For a magnetic storm
showing a maximum value of the magnetic index $K_p$ equal to 9, Ferraro (15) deduces the atom density in a cloud of corpuscles to be $40 \text{ cm}^{-3}$, although elsewhere he suggests (16) an upper limit of $100 \text{ cm}^{-3}$.

We suggest that these two effects which can contribute to an increase in the sky brightness after a flare, i.e. an aurora or scattering from temporary corpuscular radiation, may be distinguished by the change in the polarization of the sky light. If the extra light is auroral in origin, it would be unpolarized; whereas if it is due to electron scattering, it would be strongly polarized. Of course, such a separation is only practicable in tropical regions*, where aurorae are very infrequent.

Fig. 10.—Geometry of the emission of a corpuscular stream on July 7. Projection on to the plane of the ecliptic.

The increase in the brightness of the zodiacal light.—It seems significant that when the zodiacal light increases in brightness its position in space remains unchanged. The position of the zodiacal light cone, between the ecliptic and the invariable plane of the solar system, suggests that its source is a permanent feature of the solar system and is primarily gravitationally controlled, i.e. that free electrons are not an important contribution. This is supported by our spectroscopic measurements. If the light cone does not move when it brightens, following a solar disturbance, it seems unlikely that the extra light comes by electron scattering. We now examine the suggestion that this extra light is due to a fluorescence of the dust particles caused by collision between the high speed protons of the corpuscular stream and the dust particles of the zodiacal cloud.

To investigate the possibility that such a mechanism is of importance, we calculate the expected increase in brightness of the zodiacal light assuming that when a proton contained in the corpuscular stream collides with a dust particle a certain fraction of its kinetic energy is converted into energy of radiation in the visible spectrum. We neglect the electrons because of their small kinetic energy. Because of the various uncertainties, the calculations are necessarily very crude.

* This method of separation will be attempted during an Oxford–Cambridge expedition to Chacaltaya in 1961.
In the calculation we assume that the corpuscular emission has a density of 300 protons cm\(^{-8}\), which is independent of distance from the Sun, corresponding to our estimate of an electron density of 300 cm\(^{-3}\), and that the corpuscles are travelling at a speed of \(4 \times 10^8\) cm sec\(^{-1}\). Such a velocity as this has been suggested by Meinel (17) on the basis of studies of the broadened Hz line in the spectra of aurorae.

We also need the total cross section \(\Lambda\), of all dust particles in unit volume of interplanetary space. In the calculation of this we anticipate a result from Paper IV of this series, where it is supposed that the distribution of particle size is given by the relation,

\[ n(a)da = C a^{-p} da \]

where \(n(a)da\) is the number of dust particles having radius between \(a\) and \(a + da\). We suppose also, that the space density of dust particles varies with distance from the Sun as \(r^{-2}\).

Following the methods of Paper IV, we find that proton impact on the dust cloud gives an increment in brightness at elongation \(\epsilon\) equal to

\[
1.3 \times 10^3 \pi R f \csc^2 \theta + 1 \int_{\theta_1}^{\theta_2} \sin^2 \theta \, d\theta \int_{\alpha_1}^{\alpha_2} C a^{-p} da \quad \text{erg sec}^{-1} \text{cm}^{-2} \text{sterad}^{-1}
\]

where \(f\) is the fraction of the kinetic energy of the protons which is converted into radiation in the visible spectrum on collision with a dust particle. Evaluation of this expression, with \(C = 4.28 \times 10^{-30}\), \(R = 1.5 \times 10^{13}\) cm, \(a = 4 \times 10^{-5}\) cm, \(\alpha = 1\), \(p = 5\), leads to an increment which is only \(f/100\) of the brightness of the zodiacal light at elongation 35\(^\circ\). If \(f < 1\) we conclude that this mechanism is not able to explain the observed increment.

We are faced here with an apparent contradiction. After a solar flare there is apparently a brightening of the zodiacal light which must surely be attributed to increased emission from the zodiacal dust cloud. If the increased emission is due to fluorescence, we require a proton density which is greater than the maximum electron density permitted by the changes in the night sky brightness. A way out of this difficulty could be to suppose that the corpuscular stream contains a high proportion of neutral hydrogen which does not scatter solar radiation, but which can excite fluorescence. The calculations of Kahn (18) of the ionization of hydrogen in a corpuscular stream do not support this view. Yet, as we have mentioned already, Biermann has suggested that the observed accelerations of ions in comet tails can be accounted for only by assuming a density of corpuscular radiation of between \(10^3\) and \(10^5\) cm\(^{-3}\), the latter corresponding to an intense storm. We do not believe that such high densities of free electrons can exist in interplanetary space because unless they occur in very thin clouds the resulting increase in sky brightness could hardly escape detection. If Biermann's hypothesis is correct a corpuscular stream must contain a high proportion of neutral hydrogen. This is just the condition that we require to explain the increase in zodiacal light brightness through fluorescence without a large increase in sky background through electron scattering.

Conclusions.—We find that following a solar flare there is an increase in zodiacal light brightness and also an increase in the brightness of part of the sky. The increase in sky brightness is attributed to the temporary emission from the Sun.
of a beam of corpuscular radiation of density 300 electrons cm\(^{-3}\), and this view is supported by the colour of the increment in sky brightness and the place in the sky where the increase occurs. The increase can scarcely be due to an aurora because of its colour and because of the rarity of aurorae at the low geomagnetic latitude of 3°S.

The increase in brightness of the zodiacal light is not accompanied by a shift in its position, which suggests that the extra emission is from the interplanetary dust cloud. This extra emission cannot be due to interaction between the dust cloud and the protons of the corpuscular stream because these carry insufficient energy. While it is possible that the increase is due to fluorescence of the interplanetary dust under the action of short wavelength radiation, the scarcity of the data precludes adequate discussion of this hypothesis.

References

(3) E. G. Brenner, Observatory, 19, 206, 1896.
(9) A. Searle, Annals Harvard College Obs., 19, 165, 1893.
(18) F. D. Kahn, M.N., 110, 483, 1950.