Observations of the Mutual Phenomena of Jupiter: The Volcanic Hot Spots on Io

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I. Io, the Odd Satellite

The anomalous nature of Io (i.e. its multihued surface, high albedo, red colour, and absence of H_2O ices) was recognized in the early 60's (Moroz, 1961). A decade later, a brightness temperature of ~ 128 K was measured at 20 μm, which corresponds to the equilibrium temperature expected for a slowly rotating body of Io's albedo at its distance from the sun. However, quite surprisingly, measurements at 11 μm and 8.4 μm gave values of 138 K and 149 K, respectively. Sinton (1973) invoked the presence of an NH_3 atmosphere to account for these dissimilar results, but this explanation was later on ruled out by near-infrared spectroscopy (Fink et al., 1976). Also, eclipse observations revealed that Io cooled down to 102 K at 20 μm at the end of a total eclipse, but only to 125 K at 11 μm (Morrison, 1977). Furthermore, an intense brightening was observed at 5 μm at an orbital phase angle of 68°: the emission mechanism was not understood, but was thought to be probably due to an interaction with Jupiter's magnetosphere (Witteborn et al., 1979). Several photometric monitoring campaigns were then undertaken, in order to shed some light on Io's mysteries: they led to think that its variability was depending on wavelength, but no satisfactory explanation for such a property could be given (see for instance, Sinton et al., 1983 for a summary of the photometric characteristics).

Then, the 2 Voyager spacecraft arrived in Io's vicinity and unveiled part of the mystery: during the encounters, nine variable plumes (60–300 km high, with velocities of 0.5–1 km/s), ten major hot spots, and a transient SO_2 atmosphere were detected, above active vents on a young, craterless volcanic terrain, with numerous dark calderas and surface flows, which indicated vigorous, sustained eruptive activity. The volcanoes led to new thermophysical parameters, and provided a link among much of the accumulated disparate ground-based data on Io: the hot spots (whose radiation is not modified during an eclipse) produce the outbursts which are observed in the near-infrared (especially at 5 μm), and affect the photometry more at 11 μm than at 20 μm. Also, the volcanic activity is responsible for the anomalous dehydration of the surface, and accounts for the unexpected concentration of sulfur and sulfur compounds. Moreover, it can explain the apparent ionian source of sulfur and oxygen ions to the Jovian plasma torus.

This volcanism has been understood as resulting from internal heating of Io by a very large tidal dissipation (Peale et al., 1979), with an additional energy source in the Joule heating by tremendous electrical currents (Ness et al., 1979; Gold, 1979). However, as quoted by Johnson et al. (1984), *"since the 2 Voyager encounters, better characterization of the continuing volcanic activity on Io has remained a major challenge for planetary astronomers".*

II. The Infrared Spectrum

The major part of Io is in instantaneous thermal equilibrium with the absorbed sunlight (the temperature being highest at the subsolar point, and lowest at the limb). The remaining part of the surface (in areas scattered over the disk) are the hot spots at different temperatures: (~ 300 K for LOKI; ~ 600 K for PELE, which are the most prominent hot spots observed by Voyager). Sinton (1981) has shown that the energy coming from the hot spots is of non solar origin (the total non solar power is ~ 6 ± 1 × 10^{13} W, or ~ 2 W m^{-2}).

Then, the spectrum can be represented by 3 components, coming from:

- the reflected sunlight (1–4 μm)
- the thermal emission from the hot spots (4–12 μm)
- the thermal emission from the passive, insolation-heated, surface of Io at ~ 129 K, in the far IR.

Io's spectral radiance and its components as a function of wavelength is shown in Figure 1 (after Johnson et al., 1984).

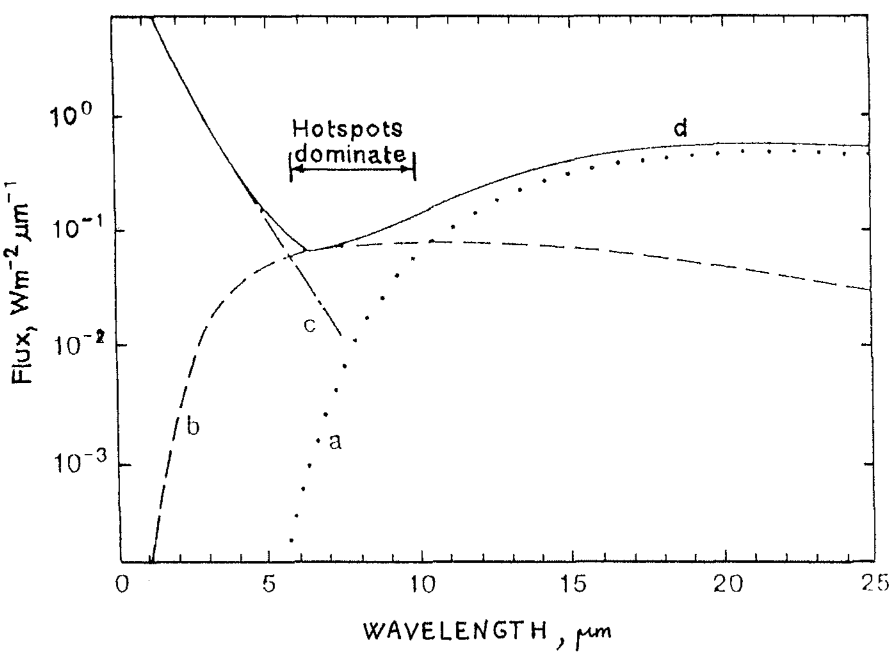

Figure 1: *Io's spectral radiance and its components as a function of wavelength: (curve a) thermal emission from the passive surface of Io (taken as an average disk temperature of 129 K); (curve b) thermal emission from the hot spots (disk centred at longitude 300° W calculated from observed Voyager hot spots); (curve c) reflected sunlight; and (curve d) the sum of the components. This figure comes from Johnson et al., 1984.*

III. The Ground-based Observations

To characterize Ionian volcanism both temporally and spatially, measurements must be made at all longitudes and latitudes, and continued for a long period of time. As the spacecraft thermal measurements are restricted to March 1979 and cover only ~ 30% of Io's surface, most of our information on volcanic activity and the magnitude of the heat flow has been provided by ground-based IR observations. Several types of experiments have been carried out:

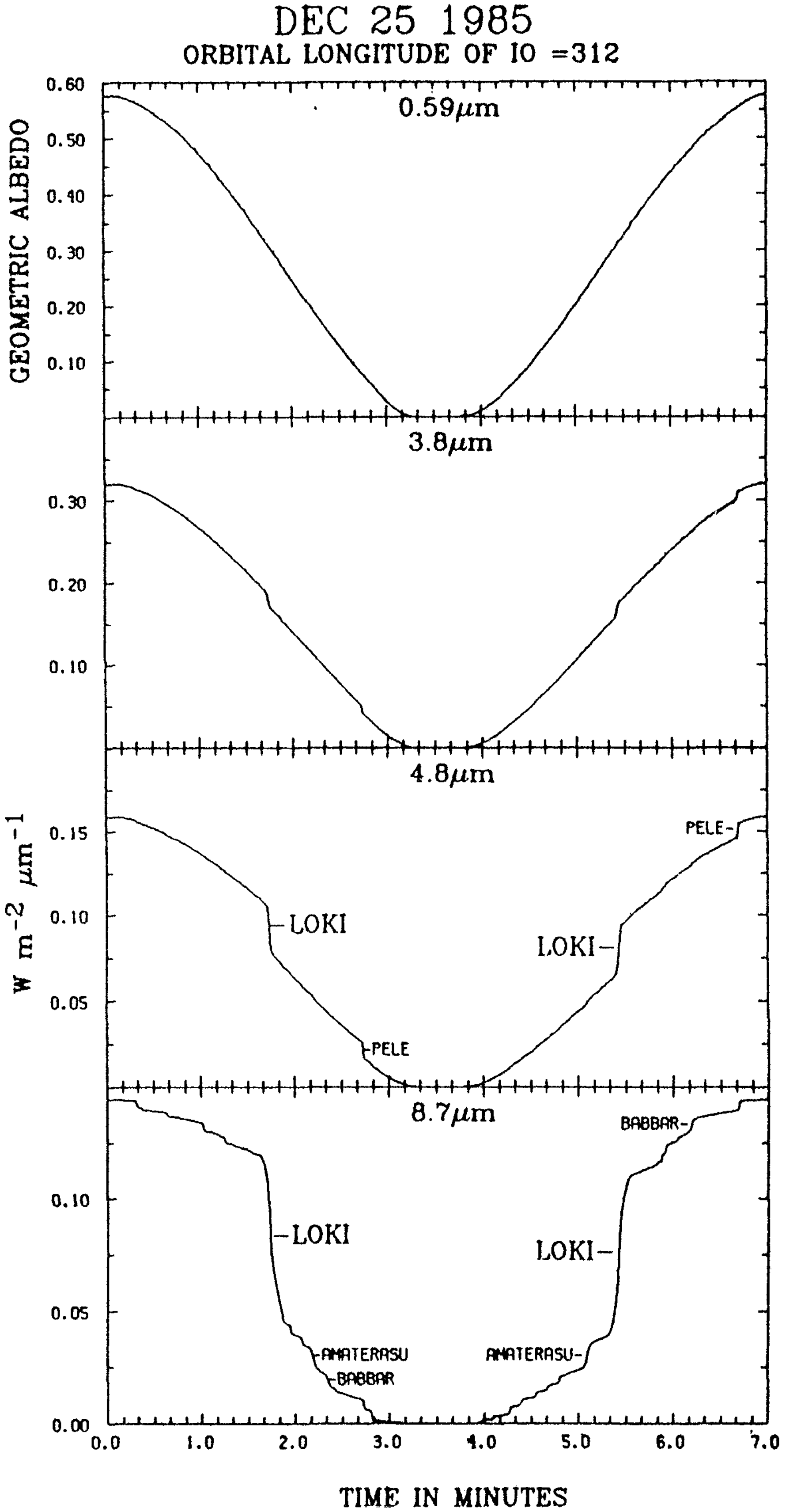

Figure 2: *Global model for the temporal occultation profiles (for December 1985) plotted against geometric albedo (0.59 μm) and against infrared fluxes. Major slope breaks due to beginning and ending occultations of hot spots are labeled (after McEwen et al., 1986).*

A. Eclipses

As a substantial fraction of the emitted radiation during an eclipse arises from hot spots, such events are propitious for studying the volcanic activity. However, eclipses are always restricted to the same hemisphere (270° W < L < 360° W). Furthermore, an adequate fitting of the cooling and heating curves requires complicated, vertically and horizontally inhomogeneous models, with two different albedo regimes. Therefore, the resulting positioning of the hot spots is far from accurate. Nevertheless, with this technique, Morrison and Telesco (1980) showed that the hot spot spectra can be matched by components with temperatures of 200–600 K covering ~ 1–2% of the surface. Also, Sinton et al. (1980) detected hot spots at ~ 560 K with a combined area of 5×10^{-5} of Io's disk.

B. Photometry (2.2, 3.8, 5, 8.7, 10 and 20 μm)

Photometric monitoring has confirmed that Io is a passive object reflecting sunlight at 2.2 μm, while it is variable at 3.8 and 5 μm due to emission from volcanic activity. Short-lived (several hours to one day) high-temperature sources have been detected: they are small and intermittent, and do not contribute much to the heat flow from Io (eight outbursts have been detected at T ~ 700 K, the temperature dropping markedly in the first hour or two down to ~ 300 K, and the derived area expanding from ~ 100 km^2 to ~ 5×10^4 km^2, with velocities of ~ 100 km/h). The most important result from the photometry has been to show that the IR emission arising from the volcanic hot spots on Io is strongly concentrated in a few locations (a greater brightness at 3.8 and 5 μm has also been observed on the trailing hemisphere*). It is not known yet if that implies more activity or a higher albedo which could be due to differences of surface composition.

C. Polarimetry at 4.8 μm

A disk-integrated linear polarization of ~ 1.6% has been measured. The de-

* The leading hemisphere is centred at 90° W and the trailing hemisphere at 270° W; this terminology refers to the hemisphere centred on the direction parallel (leading) or antiparallel (trailing) to the orbital velocity vector of a synchronously rotating satellite.

gree and position angle vary with Io's rotation in a manner characteristic of emission from a small number of hot spots. Data are fitted by a 3 hot spots model: Loki, Pele, and another one, unknown by Voyager (Goguen and Sinton, 1985). The position of Loki, as determined by this technique is 228° ± 3° W and 20° ± 2° N, with a temperature of T ~ 450 K and an area A ~ 3060 km^2.

D. Speckle Interferometry at 4.8 μm

With the speckle technique, it has been possible to resolve the disk and to detect an emission from a hot spot in the Loki region (60% of the total flux). The spot was located at 301° ± 6° W and 10° ± 6° N, with T ~ 400 K and A ~ 11,400 km^2 (Howell and McGinn, 1985).

In conclusion, although ground-based IR observations have yielded an estimate of the global heat flow from the hot spots (Morrison and Telesco, 1980; Johnson, 1984), there are two major uncertainties in (i) the positioning of the hot spots and (ii) their latitudinal distribution, as high-latitude features are underrepresented when viewed from earth: if the known sources are the only major volcanic centres, then current global heat-flow estimates must be revised downward. It turns out, then, that heat flow from unobserved longitudes, hot spots at high latitudes, and conducted heat flow must still be measured.

IV. The Mutual Events

The occultations of Io by Jupiter (very common) are not useful because of the atmosphere of the planet. When the Earth and the Sun cross through the orbital plane of the Galilean satellites (every ~ 6 years), a series of occultations and eclipses of one satellite by another may occur ("mutual phenomena"). In 1991, Io will be mostly occulted by Europa, whose albedo is 0.02–0.04 and which is not emissive in the near IR; this is highly favourable. Moreover, the relative velocity between Io and Europa during the occultations will be optimum. These occultations will then provide rare opportunities to achieve a spatial resolution that exceeds the diffraction limit of the telescope and which is unreachable with any other technique: speckle and polarimetry give accuracies of a few 100 km, while occultation with a 4-m class telescope allows spatial resolution of hot spots on the scale of a few tens of kilometres (to be compared to the diameter ~ 200 km of Loki).

In a first step, the observations of these mutual phenomena in the visible range of the spectrum should improve our knowledge of the dynamics of the motions of the Galilean satellites, allowing, for instance, the research of weak non-gravitational effects which are suspected but not yet detected, and therefore not included in the current theory (in particular the secular acceleration of Io). It has to be stressed that the current theory is based on observations whose accuracy is not better than 400 km. Yet, space exploration imperatively requires a more accurate positioning of the Galilean satellites! Then, in a second step, these observations combined with infrared ones should help determine the location and temperature distribution of Loki, the source(s) of excess emission in all the regions, the distribution of small, high-temperature sources, and the albedo changes of the scale of those that occurred between the Voyagers encounters.

The technique used for the observations, and the achievable results are described in the pioneering work of Go-

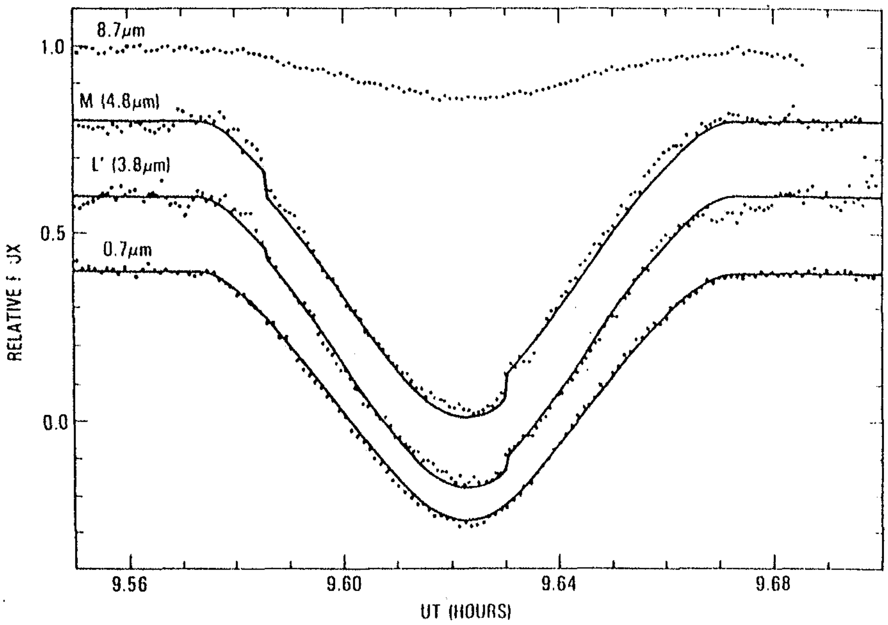

Figure 3: *Data (3 sec average/point) and global model (curves) for the occultation by Callisto on July 10, 1985. All curves have unit value before and after the occultation, but an integral number of offsets of 0.2 have been subtracted for clarity (after Goguen et al. 1988).*

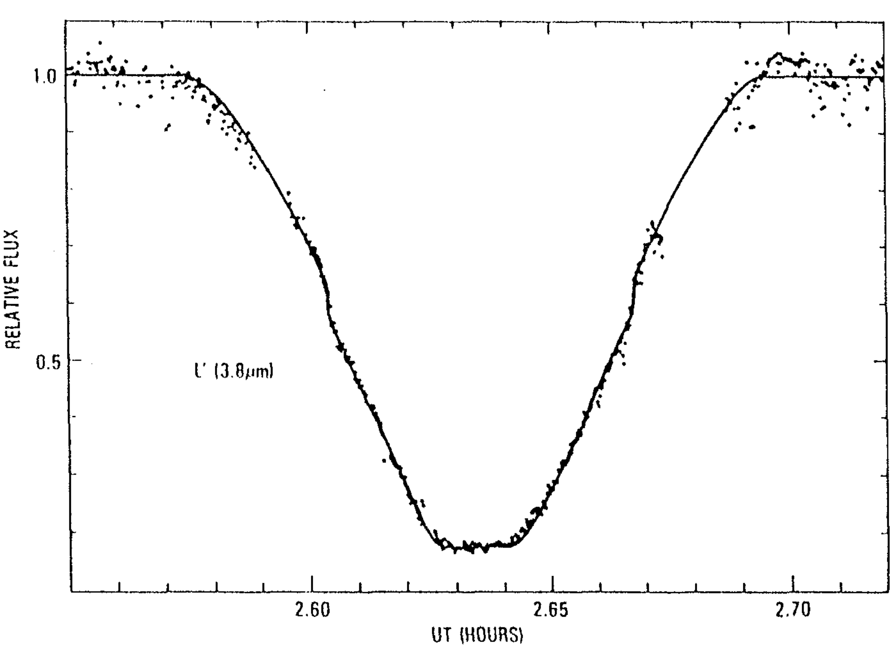

Figure 4: *Data (1 sec average/point) and global model (line) for the occultation by Callisto on December 25, 1985, obtained with the CFHT at 3.8 μm. Missing data segments and variable noise are caused by detector saturation as a result of fog in the field of view. The vertical offset near 2.603 and 2.607 hr UT are the disappearance and reappearance of the Loki region, which was included in the global model (after Goguen et al., 1988).*

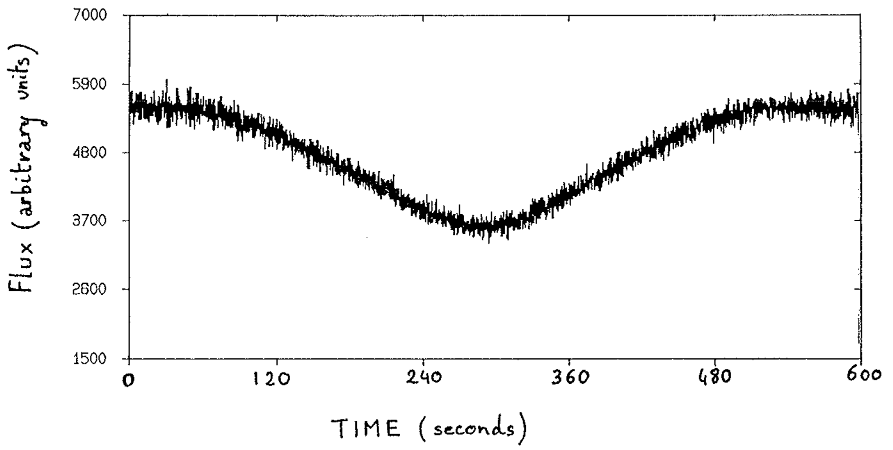

Figure 5: *Light curve obtained through the V filter during the occultation of Io by Callisto on February 15, 1991, with the ESO 50-cm telescope.*

guen et al. (1988): the combined flux of the occulting satellite and the unocculted portion of Io is tracked through a ~ 10 arcsec aperture (as Io is ~ 1 arcsec on the sky, a typical occultation lasts ~ 6 minutes but events of a few hours duration can also occur). The velocity of the occulting satellite is ~ 20 km/s at Io, and then a sampling of 0.1 seconds yields a spatial resolution of a few kms. The disappearance of a significant hot spot behind the occulting satellite limb results in a decrease in flux that lasts until the hot spot reappears. Observations are carried out at wavelengths from 3 to 10 μm: measurements at two wavelengths of the fluxes from a hot spot determine both T_{eff} and the solid angle it subtends, and then its area (the duration of the hot spot occultation gives an independent estimate of its size, if the hot spot is sufficiently large and bright). It has to be emphasized that the observations need to be obtained with a fairly high signal-to-noise ratio, which at these wavelengths can only be achieved with large telescopes (4-metre class).

Modeling the expected temporal profiles requires not only good ephemerides for the geometry of each event (the major uncertainty being the "impact parameter", which is known with an accuracy of ~ 400 km only), but also the knowledge of the albedo distribution and the photometric behaviour in the IR, which are both unknown. Furthermore, if the model were to omit the effect of hot-spot occultation on the light curves, the derived satellite positions would be affected. Therefore, a global model of the complete distribution of the hot spots is first constructed on the basis of the light curves obtained in the visible and the correlation between hot spots and low-albedo features seen in the Voyager images, assuming uniform normal reflectivities. Such a model is illustrated in Figure 2, which shows the temporal occultation profiles for December 25, 1985 as a function of wavelength, as computed by McEwen et al. (1986). Using this occultation technique, Goguen et al. (1988) have shown that the mean error in the apparent relative position of the occulting satellite is ~ 178 km. These authors have resolved Loki (with a diameter of 200 km, centred at 308° ± 1° W and 20° ± 3° N), and discovered a new spot (of ~ 20 km diameter) on the leading hemisphere: Figures 3 and 4 illustrate their notable results.

V. Results

Each event is visible only from a restricted geographical area, and therefore an international campaign had to be organized in order to make the best possible profit of these mutual phenomena. The remoteness of La Silla with respect to the other major observatories involved in this campaign makes ESO an indispensable partner in this network.

Observing time has been allocated at the ESO 50-cm telescope, to follow 13 events in the visible during period 46 and 12 during period 47. These events observable at La Silla are mostly not observable from other sites (Arlot and Rocher, 1989). On a total of 19 already passed occultations, 13 have been well observed and very nice light curves have been recorded, as can be seen in Figure 5 which displays the February 20, 1991 results. Unfortunately, the harvest concerning IR light curves is far from being as rich! Five nights only have been allocated to this programme with the ESO 1-m telescope. Observations at 5 and 8 μm had therefore to be disregarded, and it was expected that the signal-to-noise ratio of the light curves obtained at 3.8 μm be too poor to yield any significant new results concerning Io's hot spots. However, we have been trying to perform these observations, in order to confirm the feasibility of such a programme and to check the capabilities of the ESO infrared photometers. For several reasons (bad weather or too high an airmass) only two occultations could be recorded. The light curve obtained on February 20, 1991 is shown in Figure 6: although the signal-to-noise ratio is far from ideal, it can be seen from this figure that the shape of the light curve is not the expected one, if the surface of the satellite were uniform. That result gives a clear account of (i) the power of this technique, and (ii) the quality of the data which could have

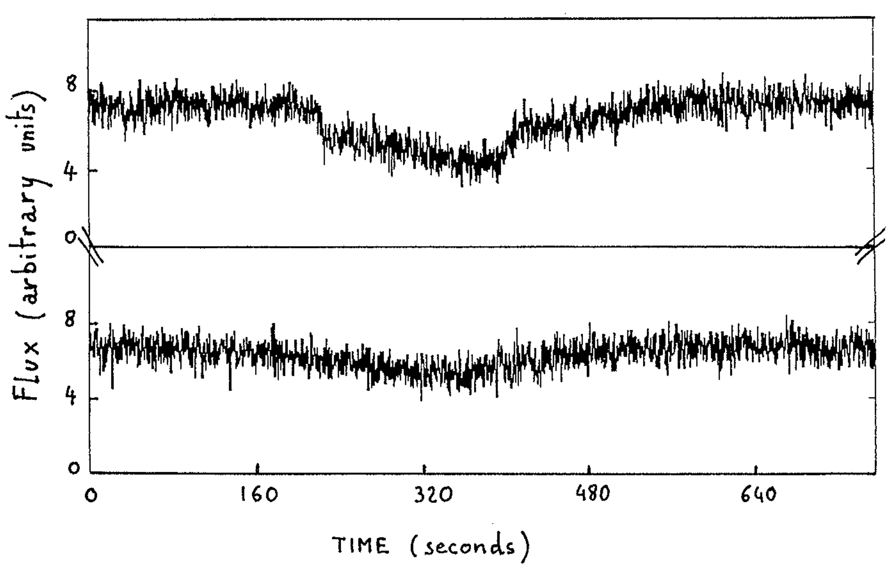

Figure 6: *Light curves obtained through the L filter (3.8 μm) during the event of February 20, 1991, with the ESO 1-m telescope: upper curve, the occultation of Io by Callisto (note the asymmetric profile); lower curve, the following (a few minutes after the occultation) eclipse of Io by Callisto.*

been obtained with the ESO 3.6-m telescope instead of the 1-m.

The high-quality results obtained in the visible at La Silla will now be combined with the results obtained from other observatories. This will lead to new position ephemerides for the Galilean satellites. There is no doubt that ESO will have played a major role in this realization.

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Splitting the Zodiacal Light

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1. Introduction

In view of the progress in the field of astronomy, in particular the ever-increasing accuracy of measurement and the development of high-resolution optics, it is an amazing fact that some of the largest phenomena in the sky have not yet been correctly described. This realization came as a surprise to us, a group of German amateur astronomers.

Some time ago, scientists of the Astronomical Institute of the University of Bochum, Germany, drew our attention to various unsettled problems concerning the inclination of the zodiacal light against the ecliptic plane. Already the first person who described this phenomenon, the well-known French-Italian astronomer Giovanni Domenico Cassini, noted an inclination of 3° against the orbit of the Earth (1). Visual, photographical and photometric observations in our century gave other results and were quite inconsistent (2). In the meantime, the Infrared Astronomical Satellite (IRAS) has shown that the zodiacal light bridge consists of individual bands within 10° of the Ecliptic. These substructures can be connected to the large number of asteroids with similar orbital parameters, leading to frequent collisions and thus to inhomogeneous concentrations of the dust (3).

2. New Observations

To obtain new and better observational results, we installed our cameras at places with low light pollution and made deep photographs of the Ecliptic. This work started in 1984 at the observatory at Jungfraujoch in Switzerland in the High Alps and ended in March 1989 at the ESO La Silla observatory.

We employed a fisheye lens (2.8/16 mm) which has a field of view of 180° over 43 mm image diagonal and which is very useful to render large- and low-contrast phenomena. As film served the T-MAX 400 emulsion from Kodak, which was forced to 1600 ISO while preserving its gradation. In this way we kept the exposure times short enough to avoid any smearing-out of the regions near the horizon, which would otherwise have exposed themselves on delicate structures in the zodiacal light. The camera was pointed to the antisolar direction and the lens was stopped down one step to have a more homogeneous illumination on the negative. Since one of our aims was to examine the position and structure of the gegenschein, the pictures were taken at times when the

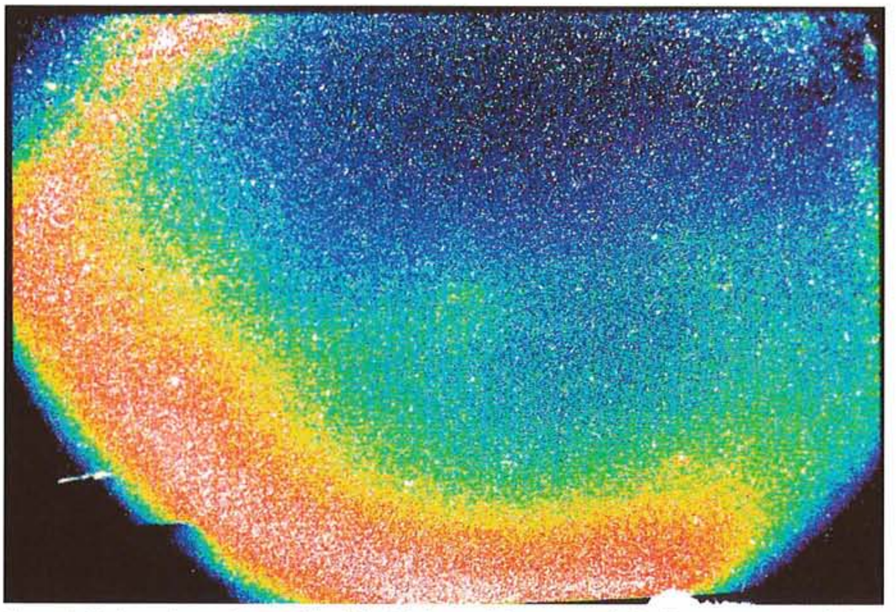

Figure 1: *False-colour picture of the light bridge and the gegenschein. Due to a strong airglow, the areas of the Ecliptic near the horizon are overexposed and the zodiacal light bridge shows a low contrast. Exposure: 60 min on March 14, 1989, 6:03 UT; objective: 4.0/16 mm.*