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Cornell University
Ithaca, New York 14853

Introduction

The linear polarization of the Kleinmann-Low Nebula in Orion exhibits strong wavelength dependence in the near infrared. Dyck et.al. (1973) and Dyck and Beichmann (1974) observed the Becklin-Neugebauer source in this nebula and found a strong increase in polarization at 10μ where the nebula also exhibits a broad spectral absorption feature frequently attributed to a silicate dust component. Shortward of the silicate feature, Loer, Allen and Dyck (1973) and Breger and Hardrop (1973) found a rapid rise in polarization increasing to a value of 26% at 1.6μ. The cited polarization angle lies in the approximate range of 100° to 115° throughout this wavelength domain; the reported errors in angle are of the order of ±5°. There also is a remarkable uniformity for the direction of polarization across the Kleinmann-Low nebula. Dyck and Beichmann carried out observations at 11.1μ across the central half minute of arc of the nebula and found a polarization of the order 10% at an angle of 87°±12°.

Circular polarization has also been found to be unusually high. Serkowski and Rieke (1973) found the circular polarization at 3.4μ to have a value of 0.9%.

P.G. Martin (1975) has made use of the linear polarization data at 10μ to place bounds on the band strength of the absorbing grain material and on the shape and degree of alignment of the grains. Dennison (1977) has reanalyzed all available data and presents a strong case for the production of polarization through preferential extinction by grains having plausibly high temperatures,

$T_g >> 6°K$. High temperatures had previously been considered a difficulty, since the dust grains had been expected to show randomized orientations at elevated temperatures--clearly inconsistent with a model in which polarization is produced by well aligned dust.

Dyck and Beichman, as well as Dennison, explain the polarization observed at $\lambda \lesssim 13\mu$ in terms of absorption of background radiation, by cooler foreground dust within the Kleinmann-Low Nebula. Elongated dust grains aligned by local magnetic fields are thought to absorb anisotropically to produce the observed polarization.

If this mechanism is indeed prevalent, one may expect to detect emission from these same oriented grains at much longer infrared wavelengths, and this radiation should then show a direction of polarization perpendicular to that seen in the near infrared. Our intention in planning new observations of the Kleinmann-Low Nebula was to search for this polarization in emission, in four wavelength bands $16 \lesssim \lambda \lesssim 120\mu$.

Instrumentation

Our flight dewar contained a gallium doped germanium photoconducting detector, in front of which any one of four different filters could be placed by rotating a cooled filter wheel. Fig. 1. shows the optical configuration in which observations were taken during flight. Light entering the NASA C-141 Airborne observatory's f/17, 91 cm bent Cassegrain telescope first impinges on the primary and then onto a wobbling secondary mirror which permits alternate viewing of source and 'blank' sky. The radiation then is reflected off a diagonal mirror into a direction perpendicular to the primary optical axis. From there the light proceeds to a dichroic mirror, where the visible light is transmitted to a fiber optics bundle for focal plane guiding via a television monitor, reflected infrared radiation passes through a polarization analyzer (Cambridge Physical Sciences model IGP 223) and then enters the liquid helium dewar through a polyethylene window. Thereafter the radiation proceeds through a 4mm circular aperture at the focal plane of the telescope, hits another diagonal mirror which directs the beam at right angles, and passes through one of the filters on the filter wheel. It then is incident on a field mirror which finally focusses the radiation onto the liquid helium cooled detector. The 4mm aperture defines a $\sim$1' beam on the sky. The throw of the wobbling secondary chopper produces two beams separated by $\sim$2.5'. The filter characteristics are shown in Table 1. The long wavelength cut-off beyond filter 4 is determined by the detector band gap. At very short wavelengths the detector response drops rapidly. We checked for light leaks outside the nominal bandwidths, both with a far infrared monochromator as a source, and with a high intensity lamp, and in no case could a leak be found outside the filter band of interest.

In the laboratory the instrument was tested both with and without the dichroic mirror, and its polarization characteristics were determined with the use of a liquid nitrogen blackbody source. The intrinsic polarization characteristics without the telescope are shown for each filter bandwidth in Fig. 2. In this figure, points L and P label the laboratory data. Points L were obtained in our laboratory at Cornell University. Points P are preflight calibrations made at the NASA Ames Research Laboratory. The roughly one percent differences in these two calibrations are partially indicative of the reproducibility of the equipment at the time of these first flights. The differences between these readings and the polarization of Jupiter observed during our flights--points labeled J-- may be explained by differences in the polarization produced in the bent Cassegrain telescope and in our laboratory source. The Orion data are indicated by points labeled O, in Fig. 2.

When two identical polarizers of the kind we flew are crossed, a faction of the incident radiation still reaches the detector. We define a polarizer efficiency by

$$E = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad ,$$

where I_{max} stands for the maximum light received through a pair of polarizers, and I_{min} is the minimum light transmitted. For filters 1, 2, 3, and 4, respectively, this gives 63%, 85%, 91% and 90%. The polarizer orientations for minimum transmission were identical for all four filters to within a degree.

Observations

Observations using the Kuiper observatory's bent Cassegrain telescope were carried out at altitudes of 12 km on the nights of November 18 and 22, 1976. On November 18 the flight plan had called for an initial period of calibration on Jupiter, followed by a period of observations on Orion. Approximately one hour had been planned for observations on these two objects, but unfortunately the Jupiter observations had to be cut short because of an unforeseen change in the winds. Because of this, calibration data were obtained only for Filter 2 (28-48μ) on this particular date. We then immediately switched over to observations on Orion, which were carried out for a duration of an hour. Since we only had calibration data for Filter 2, we started out with the intention of carrying out the Orion observations primarily with that filter. Approximately 45 minutes

Table 1

Filter Characteristics

Filter Number	Filter components	Approximate waveband of maximum transmission
1	a) 1.3 mm thick KRS-5 with 0.01mm Polyethylene on each side b) 2mm thick KCl c) A 15.7-26.7μ interference filter on a silicon substrate	16-26μ
2	a) 8-16μ diamond dust on polyethylene film, applied to 1 mm thick sapphire b) 1 mm thick AgBr	28-48μ
3	a) Same KRS-5 filter as above b) 1.5mm CaF_2 with 0.01mm polyethylene on each side.	44-72μ
4	a) 2.2mm BaF b) 0.1mm black polyethylene	71-115μ

into the run, however, we decided to investigate the polarization as seen through Filters 1, 3, and 4 as well. Fortunately we were able to arrange for additional calibrations four days later in the course of an engineering flight that had been planned for that day. On this second flight Jupiter was viewed through all four filters, and at least the results for filter 2 could be compared to the previous flight's results: The reference polarization of Jupiter on both flights was close to 7.8% with a polarization direction of 62.2°. The scatter in the data points is low, as seen in Fig. 2.

A complete run taken with one filter in place consisted of data taken in eight different polarizer positions spaced 45° apart. A ninth reading taken after eight 45° displacements of the polarizer gave a consistency check on the first measurement obtained in the first polarizer position. For each polarizer position two positive-negative beam differences were taken for a total of two data points. A complete measuring cycle therefore consisted of measurements successively in the positive, negative, negative and positive beams, for each polarizer position. These two differences (positive-negative and negative-positive) tend to be consistent, except that on part of the run the telescope pointing had to be manually corrected after beam switching, and some of that correction inadvertently affected the first of each pair of similar readings obtained. In these situations we have selected the second reading of a pair as the more representative data point. The strip chart recordings obtained give us an after-the-fact record of where the corrections should be made, since signal strength buildup can be seen directly as the telescope pointing was being corrected.

After data on a source had been obtained in all eight polarizer positions, a new filter was switched into place inside the dewar, and the procedure was repeated for the wavelength range transmitted by this new filter.

The uncertainty of our results is best measured in terms of the scatter of individual points shown in Fig. 2. Generally this scatter is considerably higher than one would expect on the basis of the rather small variation in individual signal strength measurements, judged by differences in successive positive-negative, negative-positive beam measurements. Such pairs of measurements showed good agreement, but when similar measurements were repeated after a complete cycle of polarizer positions, the deviation from the original readings was several times higher than the difference between the measurements in each pair. . These changes which must be symptomatic of some long term drifts, possibly in atmospheric transmission or in chopper stability, are chiefly responsible for the scatter of data points in Fig. 2. Data obtained with filter 1 show particularly large scatter, perhaps because the sensitivity of our detector drops rather rapidly in this spectral range.

Results

The most striking result of our observations is readily summarized: the polarization--if any--that characterized the radiation in the three longest wavelength filter positions is small. Relative to Jupiter, the polarization at wavelengths beyond 30μ appears to be at most ∿2%±2%.

The noisiest observations by far are the measurements obtained in Filter position 1, 16-33μ. Here the difference in readings between Orion and Jupiter amount to ∿7%, but since the polarization efficiency is only 62% at that wavelength, the implied intrinsic polarization of the Kleinmann-Low Nebula is about 10%. Since the quality of the data is poor, we regard this value as a rather poor upper limit. A repeated set of observations will provide greatly improved data.

For the moment we have to assume that Jupiter is unpolarized at the long wavelengths observed. As more observations accrue, with Jupiter observed in different parts of the sky, this assumption will be verifiable. For Filter 2 we have observations taken with Jupiter in quite different parts of the sky--once at night and once in the day time--and the results are consistent with zero polarization at these wavelengths.

Discussion

The most convincing result of our observations is the low polarization observed at long wavelengths. The observations of Breger and Hardrop (1973), Dyck et.al. (1973) and Dyck and Beichman (1974), imply that "silicate" grains are well aligned over a region around the Kleinman-Low Nebula extending at least 1/2' across the sky, in the outer parts of the nebula facing toward us. Beyond this layer, however, the dust must be ineffective in producing long wavelength polarization since so little polarization is observed. Our long wavelength data can be made compatible with observations at shorter wavelengths only if there is very limited grain alignment in much of the nebula or else if the nebula is optically thick at 100μ. This conclusion is a consequence of the following quite general argument:

Consider a nebula in which the extinction is τ_x and τ_y along orthogonal directions x and y, both perpendicular to the line of sight taken to be the z-axis. At the long wavelengths under discussion here, the extinction is entirely due to absorption (as contrasted to scattering) for all practical purposes. Under these conditions a uniform cloud would exhibit an amount of polarization in emitted radiation (Dennison, 1977)

$$P_e = \frac{[1 - \exp(-\tau_x)] - [1 - \exp(-\tau_y)]}{[1 - \exp(-\tau_x)] + [1 - \exp(-\tau_y)]} = \frac{\sinh(\frac{1}{2}\Delta\tau)}{\exp(\tau) - \cosh(\frac{1}{2}\Delta\tau)} , \quad (1)$$

where

$$\Delta\tau \equiv \tau_x - \tau_y \quad \text{and} \quad \tau \equiv \frac{1}{2}(\tau_x + \tau_y) \,. \tag{2}$$

At very long wavelenghts where the optical depth of the cloud might be expected to approach zero, $\tau \to 0$,

$$P_e \sim \frac{\Delta\tau}{2\tau} \,.$$

With this same formalism, the polarization produced by absorption of radiation passing through this medium and originating from an unpolarized background source can be expressed as

$$P_a = \frac{\exp(-\tau_x) - \exp(-\tau_y)}{\exp(-\tau_x) + \exp(-\tau_y)} = -\tanh\left(\frac{\Delta\tau}{2}\right) \,. \tag{4}$$

For small values of $\Delta\tau$, $P_a \sim -(\Delta\tau/2)$.

We have to bear in mind that optical depth is a function of wavelength. At 10μ in the 'silicate' absorption feature Aitken and Jones (1973) and Gillett et.al. (1975) propose that $\tau \sim 3$. The observed polarization is of the order of 15% at this wavelength, and we conclude that $\Delta\tau$ should have approximately twice this value. This gives $\Delta\tau \sim 0.3$ and $\Delta\tau/2\tau \sim 0.05$ at 10μ.

Dennison (1977) has calculated the far infrared ($\lambda > 40\mu$) polarization expected if the nebula is homogeneous but optically thin and finds it to be in the range of 5 to 8%. He assumes that the grains have properties of the type exhibited by Lunar dust (Perry et.al. 1972).

We have to ask ourselves why our observations show a substantially lower polarization. For an optically thin cloud, low polarization can occur only if the grain orientations are randomized, perhaps through turbulence, in the cloud's interior.

If the grains were not randomly aligned, we should see polarized emission by the grains along the entire line of sight, and hence would expect systematically polarized emission.

Dennison (private communication) has pointed out that one might expect the difference between gas and dust temperatures to fall drastically in the dense, $n_{H_2} \gtrsim 10^6\ cm^{-3}$ (Kutner et.al. 1976), central portions of the Kleinmann-Low Nebula so that dust alignment would no longer be maintained even in intense magnetic fields.

Another possible explanation could be invoked if the cloud did not become optically thin at longer wavelengths. In that case P_e approaches a value $(\Delta\tau/2)\exp-\tau$, for $\Delta\tau/2 \ll 1$, and this value of P_e can then be much lower than 0.05. Observations by Forrest et.al. (1976), Lemke et.al. (1974) and Werner et.al. (1976) do not entirely rule out a nebula that is optically thick even at 100μ. Turbulence, temperature equilibrium between gas and dust, or substantial optical depth at the center of the Kleinmann-Low Nebula, all could account for the low polarization observed at long wavelengths, and still be consistent with significant polarization observed at 10μ.

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Figure Captions

Fig. 1. Schematic diagram of the polarization analyzer mounted on the Kuiper Observatory 91 cm telescope. Radiation entering the telescope is reflected off the primary and chopping secondary mirrors before being reflected out the side of the telescope. The f/17 beam is then incident on a dichroic beam-splitter which transmits visible light to the television guiding system by means of a fiber optics bundle. Far infrared radiation reflected by the dichroic element passes through a polarization analyzer which can be rotated in steps. The radiation then enters the dewar, passes through a focal plane stop and one of the four cooled filters mounted on a filter wheel, and finally reaches the detector via a field mirror.

Fig. 2. Raw polarization data obtained with each of the four filters. North defines the 0° direction, East is at 90°. L represents the polarization obtained with the instrument viewing a laboratory blackbody source after one 90° reflection that is 180° out of phase with the 90° reflection in the 91 cm telescope. P stands for preflight tests with the same test setup, and shows the reproducibility of the system after shipment across the country. J represents the polarization measured for Jupiter and O the polarization for the Kleinmann-Low Nebula in Orion. In this paper we assume that Jupiter is unpolarized and that the polarization measured is instrumental. Considerable polarization characterizes far infrared filters of the type currently available. We have not placed error

bars around the individual points because they might be misleading. Generally the individual data points represent two separate sets of differences, on and off the source; these tend to agree with each other far better than with data taken some minutes prior or later. Such drifts apparently account for the larger scatter observed among the individual points.

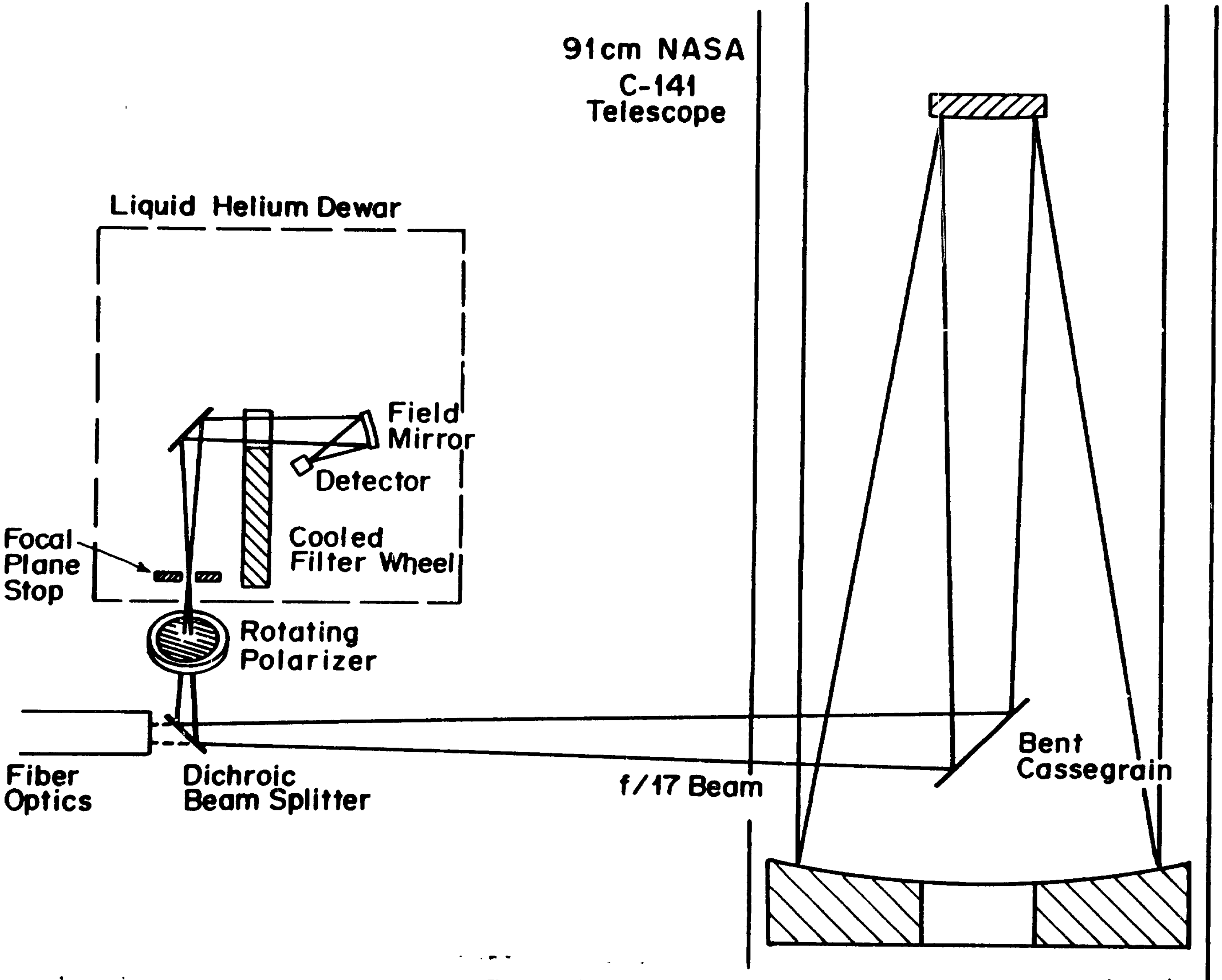
91cm NASA
C-141
Telescope
Liquid Helium Dewar
Field
Mirror
Detector
Focal
Plane
Stop
Cooled
Filter Wheel
Rotating
Polarizer
Fiber
Optics
Dichroic
Beam Splitter
f/17 Beam
Bent
Cassegrain

Figure 1

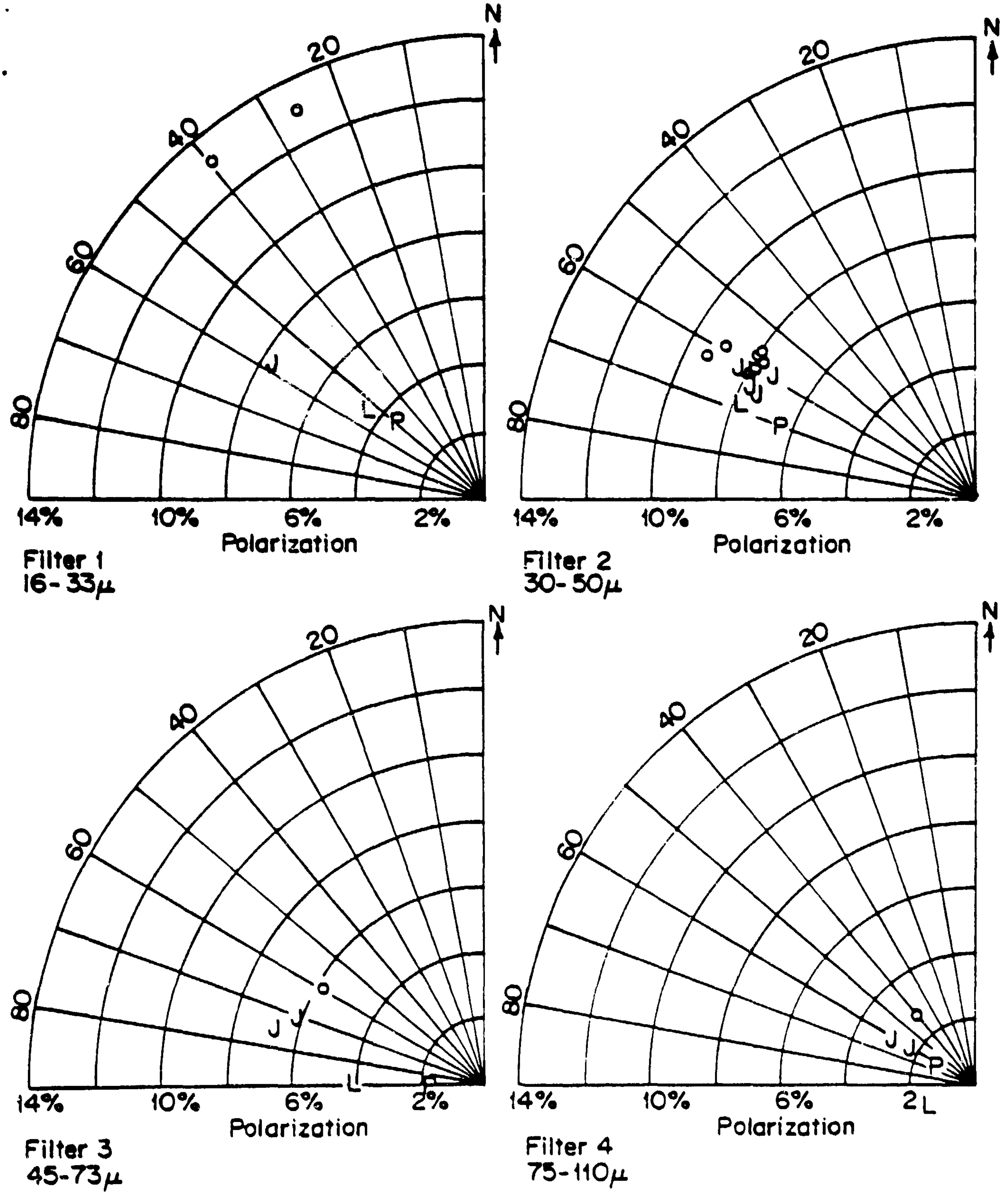
N
20
40
60
80
14%
10%
6%
2%
Polarization
Filter 1
16-33μ
Filter 2
30-50μ
Filter 3
45-73μ
Filter 4
75-110μ
J
L
P

Figure 2