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MONOCHROMATIC POLARIZATION MEASURES OF COMET IKEYA-SEKI (1965f)

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Summary

Monochromatic measures of polarization of Comet Ikeya-Seki (1965f) at 3 890 Å, 4 300 Å, 4 740 Å and 5 875 Å are described. The relative contributions of emission and continuum to radiation transmitted by the filters at 3 890 Å and 4 740 Å are evaluated. The polarization at phase angle 90° of the CN (0,0) band is 6·9% while that of the C_2 (1,0) band is 10·7%, in close agreement with the theoretical values for resonance fluorescence. The polarization value of the continuum is 24·7% at phase angle 90°, while for the same phase angle, a measure of the polarization in the tail, 3′ away from the head, is 13·6%. The agencies responsible for the continuum in both head and tail are likely to have a difference in the major constituent. The role of ices and iron particles as scattering agencies is discussed.

1. *Introduction.* The polarization of light from comets was detected by Arago nearly a century and a half ago. Subsequent studies of cometary polarization carried out on the bright comets of the nineteenth and early twentieth centuries employed visual techniques that utilized wide wavelength regions. The pioneering effort of Öhman (**1**) on Comet Cunningham (1940c) and Comet Paraskevopoulos (1941c) provided the first monochromatic measures of polarization of the light from the head of a comet. Öhman made these measures photographically with a polarigraph and objective prism on an astrographic telescope. This investigation facilitated, for the first time, the distinction between the polarization contributions of the continuum and that of the emission bands.

The bright comets of 1957, Comet Arend-Roland (1956h) and Comet Mrkos (1957d) enabled the first attempts of polarization measurement with the photoelectric technique. Bappu & Sinvhal (**2**) measured monochromatic polarization in both comets, while Hoag (**3**) and Johnson (**4**) utilized wide band techniques for the measurement of polarization in Comets Mrkos and Arend-Roland respectively. Blackwell & Willstrop (**5**) measured photographically, monochromatic polarization in Comet Arend-Roland. Photographic measures in extended wavelength intervals were also made by Blaha *et al.* (**6**).

We now confine our attention to the monochromatic measures. Öhman's results indicated that polarization in the emission bands agreed with the value expected in the case of a fluorescent origin of the radiation. The continuum polarization had the value indicative of scattering by dust particles in the cometary head. Bappu & Sinvhal utilized interference filters, having a width at half intensity of 80 Å, to isolate the wavelength regions at 4 300 Å, 4 800 Å, 5 000 Å and 5 890 Å. Their measures of Comet Arend-Roland were exclusively of the cometary continuum. However, for Comet Mrkos, they were able to measure the polarization contribution of the Na emission. The high value obtained was in agreement with the theoretical value for sodium resonance radiation. Blackwell & Willstrop isolated the region of the (0,0) band of CN with a filter that had a width at half intensity of 370 Å. Their value of 13·7% is reasonably close to the expected value for fluorescence. The continuum isolated with a filter of half width 226 Å gave a value indicative of scattering by dust.

2. *The observations.* Our observations of the polarization of Comet Ikeya-Seki were made with a conventional photoelectric photometer and rotatable polaroid attached to a 20-cm refractor. Of the several apertures available in the focal plane diaphragm we utilized one of diameter 1·8′ for polarization measures. Bausch and Lomb interference filters isolated the wavelength regions 5 875 Å, 4 740 Å and 4 300 Å, while the region of 3 890 Å was isolated by a Schott and Genossen interference filter loaned to us by Dr Gyldenkerne for the 1963 Zeta Aurigae programme. All filters were calibrated in our laboratory with a photo-electrically recording monochromator. These characteristics are listed in Table I. The analyser was a selected polaroid mounted with its axis of rotation coincident with the optical axis of the photometer. The polaroid is capable of rotation in six equal steps of exactly 60 degrees. In utilizing Fessenkov's three position method, one obtains both the magnitude of the polarization and the orientation of the plane of vibration of the incident light, by measuring the intensity of light transmitted through three successive 60° steps of the polaroid. The deflections measured from the recorder tracings were corrected before the final polarization values were calculated. These correction factors were obtained by measuring bright nearby stars that exhibit no polarization. The correction factors compensate for instrumental sensitivity differences for each position of the polaroid. The ones used for Comet Ikeya-Seki are given below in Table II. The measured intensities also yield the angle between the plane of vibration of the incident light and that of

Table I

Interference filter characteristics

Type of filter	Schott and Genossen	Baird Atomic	Baird Atomic	Baird Atomic
Intended for	CN (0,0) at 3 888 Å	Continuum at 4 300 Å	C_2 (1,0) at 4 737 Å	Continuum at 5 875 Å
Peak transmission wavelength	3 859 Å	4 310 Å	4 720 Å	5 875 Å
Peak transmission T_0	33·5%	65%	63%	52%
Full width at $T=0{\cdot}8\ T_0$	42 Å	57 Å	27 Å	39 Å
Full width at $T=0{\cdot}5\ T_0$	94 Å	75 Å	46 Å	66 Å
Full width at $T=0{\cdot}3\ T_0$	132 Å	88 Å	62 Å	84 Å
Full width at $T=0{\cdot}2\ T_0$	163 Å	97 Å	71 Å	97 Å
Full width at $T=0{\cdot}02\ T_0$	273 Å	133 Å	124 Å	163 Å

Table II

Correction factors used for Comet Ikeya-Seki (1965*f*)

Polaroid position I	Polaroid position II	Polaroid position III
1·000	0·9854	0·9910

the polaroid in its first position. The orientation of the polaroid in the photometer was determined by a laboratory arrangement. In transferring this orientation to the telescope we believe, that the error does not exceed 2°.

On each night several sets of deflections were obtained at each wavelength. These were flanked by similar three-position measures on the sky background. Our observations had to be delayed until 1965 November 4, in order to avoid the polarization of the moonlight sky. We could not pursue polarization measures after November 20, because the comet had become too faint for our instrumentation.

TABLE III

Monochromatic polarization values of Comet Ikeya-Seki (1965*f*)

Date in November	Phase angle	Position angle of intensity equator, β	Amount of polarization 3 883 Å	4 310 Å	4 740 Å	5 875 Å	Position angle of plane of vibration, α
3·974	66° 54′	88° 15′	—	19·8%	12·5%	14·7%	0°
4·972	66° 13′	88° 42′	—	17·9%	—	—	6°
14·974	59° 31′	94° 12′	8·1%	—	10·3%	—	17°
15·948	58° 50′	94° 51′	4·0%	18·9%	8·2%	—	12°
16·974	58° 09′	95° 32′	6·6%	—	8·6%	—	36°
19·952	56° 04′	97° 51′	3·5%	—	—	—	38°

We give in Table III above, the polarization measures of Comet Ikeya-Seki. Along with the value of per cent polarization and the position angle of plane of vibration α, for each day, we list the phase angle as well as the position angle of the intensity equator β. In Table IV, we give the P_{90} values for the different radiations transmitted by the filters. We assume that the relation between the phase angle and the amount of polarization is

TABLE IV

P_{90} *values for Comet Ikeya-Seki* (1965*f*)

Wavelength (Å)	P_{90} mean value (%)
5 875	17·9
4 740	13·4±1·0
4 310	24·7±1·5
3 883	7·8±1·7

$$P_\theta = \frac{P_{90} \sin^2 \theta}{1 + P_{90} \cos^2 \theta}$$

where P_θ and P_{90} are the polarization amounts at phase angles θ and 90° respectively. We wish to point out that this formula is valid only for fluorescence phenomena. We use it here to represent the polarization in the continuum, only as a convenient means of extrapolation.

3. *Polarization of the continuum.* It was not possible to measure the polarization in all four wavelength regions on each day because of the limited time available for observation before twilight effects became serious. Our observations through

the 5 875 Å filter cover only one morning. Prismatic spectra obtained on that day show no trace of sodium emission that was intense on October 30 and 31. Hence the radiation reaching the photomultiplier after passing through the 5 875 Å filter originated entirely from the continuum. The width of the filter was narrow enough to exclude possible contamination by nearby C_2 emission. A value of P_{90} of 17·9% is representative of the continuum in this region for a phase angle of 90°.

The continuum in the blue was isolated with the 4 310 Å filter of half width 75 Å. The contamination in this region by band emission is negligible. The observations cover an interval in phase angle of about 8°, yielding a mean P_{90} value of 24·7%. This P_{90} value is comparable to that obtained for the continuum for Comets Arend-Roland and Mrkos by Bappu & Sinvhal (**2**).

4. *Polarization of the emission bands.* The remaining two filters transmit wavelength regions that isolate the emission bands of C_2 at 4 740 Å and of CN at 3 883 Å. These filters also admit a certain amount of the continuum radiation. Comet Ikeya-Seki had an appreciable continuum in spectra of the head (**7**). A low dispersion slit spectrogram obtained at Kodaikanal on October 31, shows the Hα line in absorption conspicuously. The spectra also show easily the presence of the Hβ line. Tail spectra of Comet Ikeya-Seki obtained by a prismatic camera indicate a whole scale dominance of continuum in the tail caused perhaps by the close approach to the Sun.

Our procedure to evaluate the contribution of the continuum to the radiation transmitted by these two filters was as follows. On one night, close to the end of our observing spell on the comet, we measured the fluxes transmitted through the filters used for polarization measures, as well as an additional filter that transmitted the continuum at 4 880 with a half width of 31 Å. We had used the known energy distribution of θ Crt given by Oke (**8**) as the standard for the flux measurements. The continuum of the comet as measured by the filters at 4 310 Å, 4 880 Å, and 5 875 Å indicated an energy distribution equivalent to that of a G8V star. We then derived the continuum radiant energy admitted by our filters at 3 883 Å and 4 740 Å using the energy distribution of Oke & Conti (**9**) for the star van Bueren number 27 in the Hyades and relating it to the comet through the 5 550 Å magnitudes of θ Crt and the comet.

We find then, that on the basis of the flux measures made on November 17.984, the CN filter admitted 94·7% of CN emission and only 5·3% of continuum as against 81% of C_2 emission and 19% of continuum transmitted by the 4 740 Å filter. The P_{90} values given in Table IV for these two spectral regions are 13·4% for 4 740 Å and 7·8% for 3 883 Å. Since the final value of polarization obtained through a filter is the weighted mean of the intensity, times the polarization of each constituent, we use the values of the continuum energy transmitted by each filter, as given above, and assume a P_{90} value of 24·7% to be the polarization of such a continuum. We then obtain the result that the polarization of the CN (0,0) emission band P_{90} is 6·9% and that of the C_2 (1,0) band is 10·7%. These are in close agreement with the theoretical values of 8–9% for fluorescence with unpolarized exciting radiation.

5. *Discussion.* Our polarization measures of the C_2 4 740 Å, CN 3 883 Å bands clearly confirm the fluorescent origin of these emission bands, a result convincingly demonstrated first, spectroscopically, by Swings (**10**) and in recent years by

Arpigny (**11**). The study of Comet Mrkos by Bappu & Sinvhal (**2**) showed the high value of polarization of the Na resonance radiation. Thus the polarization observations of Na, CN and C_2 have provided an independent confirmation of the Swings effect.

The polarization observations of the continuum cover only a restricted range of phase angle. Using the extrapolation formula for obtaining P_{90} values we obtain values of 17·1% for 5 875 Å and 24·7% for 4 310 Å. These are in agreement with similar values measured for Comets Arend-Roland and Mrkos (**2**). We, therefore, reach the conclusion that the agencies responsible for the continuum are more or less similar for the three comets. On November 16.974 we measured the polarization in the cometary tail at a distance of 180 seconds of arc from the cometary nucleus. The polarization value obtained was 9·5% or a P_{90} value of 13·6%. The position angle of the plane of vibration was 36°, similar to the value obtained on the same occasion for the radiation from the cometary head. The amount of polarization in the tail is much less than the value derived for the head through the monochromatic filters. It is interesting in this connection to study the differences in polarization between the tail and the head as obtained by Johnson for Comet Arend-Roland (**4**) and Hoag for Comet Mrkos (**3**). In a majority of cases the polarization in the tail is less than that in the nucleus. This indicates the possibility of a difference in the scattering properties of the particles responsible for the continua in both head and tail.

It would be of interest to speculate at this stage on the nature of the scattering particles in the cometary head and tail. Two features control the limits on any such interpretation. One is the excess reddening or scattering excess which differs for different wavelengths. The other is the magnitude and sign of the polarization. While one should admit that no two comets are identical in continuum scattering characteristics, by and large these characteristics have a narrow range of variation.

For Comets Arend-Roland and Mrkos the *B*–*V* colours of the heads were 0·90 and 0·89 respectively or the equivalent of a K1V star. The energy distribution of the head of Comet Ikeya-Seki was equivalent to that of a G8V star. Walker (**12**) found that Comet Baade (1954h) which had no emission bands in its spectrum, had a *B*–*V* colour of +0·80. He also observed Comet Schwassmann-Wachmann (**13**) to have a *B*–*V* colour of 0·70, during an outburst. Hence the energy distribution in the cometary continuum of the head varies over the equivalent spectral range, G8V to K1V. The *V* filter polarization measures of Bappu & Sinvhal (**2**) cover a large range in phase angle. The P_{90} value obtained with this filter is 20%. Assuming that about 25% of the radiation transmitted by this filter is of the Swan bands with a polarization of 10%, one gets an upper limit of P_{90} for the continuum admitted by the *V*-filter to be 23%. This is in fair agreement with the P_{90} values derived through the interference filters. These polarization values, over a range of angle of scattering from 103° 36′ to 138° 6′, are all positive. Hence, we utilize the magnitude and sign of polarization as well as the scattering excess, to search for clues on the nature of the scattering particles.

Liller (**14**), Swings (**15**) and Remy-Battiau (**16**) have compared cometary characteristics of polarization with those expected from theory, for dielectric spheres. Now, Whipple's icy-conglomerate model leads one to expect that the scattering agencies would be icy spheres, icy spheres with metallic or dielectric particles embedded in them, dielectric spheres of refractive index in the vicinity $n = 1·5$, and finally the metallic particles themselves with complex refractive indices. All these constituents are likely to be operative at any instant and it is also possible that their relative concentration would change from day to day as can be seen from the variations in any set of polarization observations taken at closely spaced intervals. Liller (**14**) has tabulated the polarization to be expected from each likely constituent for a phase angle of 90°, the particle size being determined from the condition that the scattering excess be equivalent to the observed values. Within a specified size-range all sizes are assumed to occur with equal frequency. The condition of positive polarization, at phase angle 90°, is satisfied only by spheres of $n = 1{\cdot}2$ and by the iron particles. While further elaborate computations would certainly enable us to produce a synthetic cometary head, we notice for the present that icy spheres and iron particles play a very impressive role in producing the scattering in the continuum.

Our observations of polarization in the tail of Comet Ikeya-Seki, 3′ away from the head, give a P_{90} value of 13% in agreement with the value for iron particles of of diameter $0{\cdot}6\mu$. Liller had shown this to be so, for comets Arend-Roland and Mrkos. It is interesting that Comet Ikeya-Seki should provide a similar result. As regards the cometary head we believe that the single scattering is predominantly by the ice spheres and ice spheres with metallic particles imbedded in them. Evaporation effects on these ices may be such as to produce a halo of the metallic particles which would finally move away into the tail, in the course of time. A fluctuating supply of the icy particles by virtue of fragmentation from below-surface explosions would necessarily exist. Comet Schwassmann-Wachmann (**13**) with its outbursts would be of considerable interest in this connection. It is likely that the comet would be less red at its ‘ minimum ’ phase than during an outburst. Polarization observations at ‘ maximum ’ and ‘ minimum ’ phases would certainly help unravel the nature of the predominant constituent consequent to the surface explosion.

A picture of iron particles in the tail agrees well with our concept of cometary debris as derived from shower meteor spectra. However, meteor trails indicate that there are differences in the material of the meteoroids of the different showers. Meteoric materials originating from old comets have larger mean densities and are less susceptible to fragmentation than those originating from newer comets. It would be of interest in this context to examine the polarization of the continuum of Comet Encke. In Comets Arend-Roland and Mrkos, the iron particles in the tail must have originated from the outer surfaces of the comets. On the other hand, Comet Ikeya-Seki during its close approach to the Sun had experienced a split, as a result of which it is most likely that an appreciable sample of the cometary interior would have gone into the tail. The interpretation of polarization in the tail in terms of $0{\cdot}6\mu$ diameter iron particles similar to the comets of 1957, leads one to wonder how the fragmentation violence could have regulated the supply of particles of these sizes, from material of supposedly greater tensile strength. A way out of the dilemma would be, that a really young comet may have material in the interior that is only slightly different from that near the outer surface. Age perhaps tends to bring in cohesive action that hardens the material in successive layers towards the centre.

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