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Photopolarimetric Studies of Comet Austin

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Abstract. Photopolarimetric observations of comet Austin with the IAU/IHW filter system were obtained on the 2.34 m Vainu Bappu Telescope (VBT) of the Indian Institute of Astrophysics, at Kavalur, India, during pre-perihelion phase on February 20,1990 and on the 1.2 m telescope of the Physical Research Laboratory at Gurusikhar, Mount Abu during post-perihelion phase on May 2 and 4, 1990. The comet appeared bluer than a solar analog during post-perihelion phase on May 2 and 4. The percent polarization shows a sharp increase towards the red on May 2 and 4. The dominant sizes of the dust particles appear to lie in a narrow range of 0.1 to 0.5 μm. Regarding the molecular band emission, CN and C_2 bands are quite strong; C_3 emission was also found to be strong though the observations on May 2 and 4 show significant variation as compared to C_2 emission. Molecular band polarization for CN, C_3, C_2 and H_2O^+ have been calculated. It has been found that emission polarization in CN, C_2 and C_3 is between 1–7% (phase angle between 107.4–109 degrees). For CN and C_2 the polarization values are close to the theoretically predicted values, but for C_3 the polarization value falls much below the theoretically predicted value. A similar result was found for comet Halley.

Key words: comet—polarization—molecules—dust

1. Introduction

Comets are generally known to have high degrees of polarization caused by two mechanisms: (1) scattering of sunlight by cometary particles and (2) fluorescence emission by cometary molecules. The molecular band polarization in comets is due to resonance fluorescence emission (Ohman 1941; Blackwell & Willstrop 1957; Bappu *et al.* 1967; Kharitonov & Rebristyi 1974; Bastein *et al.* 1986; Dobrovolsky *et al.* 1986; Le Borgene *et al.* 1987; Sen *et al.* 1988,1989) but our knowledge on this subject is very scanty. High precision photopolarimetric observations in continuum wavelengths and molecular bands are essential to compare observations with theoretically predicted values. Polarimetric observations in continuum and molecular bands were made in detail by various groups on comet Halley (Dollfus & Suchail 1987; Kikuchi *et al.* 1987; Le Borgene *et al.* 1987; Sen *et al.* 1988, 1989). Our observations (Sen *et al.* 1989) on comet P/Halley show that the polarization values for CN and C_2 agree with the theoretically predicted values, but for C_3 the polarization value falls much below the theoretically predicted value; emission from the ionic molecules: CO^+ and H_2O^+ show much higher polarization, though the errors were large (Sen *et al.* 1989). Comet Austin has given us another opportunity to study the polarization behaviour of continuum and molecular bands. Comet Austin is perhaps a new comet (Sekanina 1990) in the Oort sense. If this is the case, we have an excellent opportunity to study and compare comet Austin with a dynamically older comet P/Halley. In the present paper we present results based on our photopolarimetric observations on comet Austin.

2. Observations and analysis

Observations during pre-perihelion phase were taken on the 2.34 m Vainu Bappu Telescope at Kavalur of the Indian Institute of Astrophysics, Bangalore and during post-perihelion phase observations were taken on the 1.2 m telescope at Gurusikhar, Mt. Abu, of the Physical Research Laboratory, Ahmedabad. Observations were taken with the IHW (International Halley Watch) filter system which contains three narrow band continuum filters (UC: 3650/80A; BC: 4845/65A; RC: 6840/90A) and five narrow band interference filters covering different molecular bands (CN: 3871/50; C_3: 4060/70A; CO^+: 4260/65A; C_2: 5140/90A; H_2O^+: 7000/175A). UC, BC, RC: represent ultraviolet, blue, and red continuum respectively and the numbers after the slash are FWHM for the filter bands. A photopolarimeter which is discussed elsewhere (Deshpande *et al.* 1985) was used for observations. Data reduction and analysis has been done in the same way as was done earlier by us for comet P/Halley (Sen *et al.* 1988, 1989). Instrumental polarization was determined by observing zero percent polarization stars. In the case of the 1.2 m telescope the instrumental polarization was negligible (less than 0.05% in all the bands) and, therefore, neglected. However, when observations were made on the 2.34 m telescope, the instrumental polarization was found to be 2.25% in ultraviolet decreasing to 0.50% in the reddest wavelength. The necessary corrections for instrumental polarization were made to the Polarimetric observations with the IHW filters. We present here observations made on February 20, 1990 (pre-perihelion phase) and May 2 and May 4, 1990 (post-perihelion phase). The comet coma was observed with an aperture of 60 arcsec on the 1.2 m telescope while on the 2.34 m telescope the aperture used was 24 arcsec. Polarimetrie data along with the error in the degree of polarization (E_p) are listed in Table 1. Error estimation is discussed in section 3.

The solar type stars HD29461 and HD 191854 were observed for photometric calibration. These stars have been chosen from a list of seven IHW solar analogs (given in IHW, Photometry and Polarimetry Net, Circular 8, November 1985). The observed magnitudes of comet were converted to the standard scale of IHW, using the method discussed in our earlier paper on comet Halley (Sen *et al.* 1989). These magnitudes were converted into flux by adopting the flux conversion formulae given in IHW Photometry and Polarimetry Net, circular 3 February, 1986. On February 20, observations could not be made in UC filter as the comet was quite faint in the ultraviolet continuum and also the altitude of the comet at the time of observation was very low.

Observed polarization in molecular bands is contaminated with continuum flux which has been estimated in the same way as discussed by us earlier (Sen *et al,* 1989) and polarization due to resonance fluorescence has been calculated.

Photopolarimetric data on comet Austin in continuum and emission bands are listed in Table 1 and Table 2. Results are discussed in section 4.

Table 1. Photopolarimetric data of comet Austin in the emission bands and the continuum bands (underlined). Observed degree of polarization (%P), error in polarization (%E_P), angle of polarization vector and magnitude are listed. Flux values for the continuum bands are also listed. Observations on February 20, 1990 are done on 2·34 m VBT; other two sets of observations are done on l·2 m telescope.

Date	UT (HHMM)	Filter wave-length	%P	%E_p	Angle (θ) (degree)	Magnitude (m)	Flux (ergs/ cm^2/sec/A)
	1422	4845	7·8	3·9	118	12·67	4·302E-14
	1416	5140	11·0	1·4	35	11·45	
	1409	6840	11·2	2·3	38	11·67	3·544E-14
	1404	7000	14·3	2·2	24	11·72	
May 2, 90	2341	3650	5·55	0·30	93	8·80	2·482E-12
	2333	3871	6·25	0·19	24	5·96	
	2328	4060	3·46	0·36	20	7·69	
	2324	4260	7·18	0·41	25	8·64	
	2319	4845	10·45	0·28	23	8·04	3·018E-12
	2315	5140	6·47	0·11	21	5·50	
	2310	6840	20·43	1·5	25	8·72	5·354E-13
	2304	7000	14·56	1·19	27	8·40	
May 4, 90	2331	3650	0·97	0·81	13	8·86	2·351E-12
	2334	3871	5·95	0·40	18	6·13	
	2336	4060	2·75	0·50	22	7·13	
	2327	4845	7·04	0·55	21	8·11	2·829E-12
	2323	5140	6·41	0·17	16	5·96	
	2319	6840	18·17	1·25	18	8·36	7·500E-13
	2316	7000	13·77	1·10	16	8·03	

3. Error analysis

3.1 *Error in Polarization Measurements*

The Polarimeter works on a rapid modulation principle, the sampling rate being 1 ms and the data are processed on line with an IBM–PC. The error in polarization measurement is estimated from photon statistics using a least square solution. The error in position angle is estimated by the relation given by Serkowski (1962):

$$E_\theta = 28.65^\circ \; E_p/P \; (\text{for } E_p \ll P) \tag{1}$$

where E_θ and E_p are error in position angle (θ) and degree of polarization (P) respectively. Error in degree of polarization is listed in Table 1; E_θ may be computed using the above relation (1).

3.2 *Error in Flux Measurement*

The error in observed magnitude (including the error in extinction values and error in transformation to standard magnitude system) on May 2 and 4 is ~ 0.05 mag. At the time of observation, the comet was quite high in the sky (more than 30 degrees above the horizon). All continuum filters are free from cometary molecular emission except

Table 2. Flux in different emission bands due to molecular emission along with the background continuum contribution in the entire band in ergs/cm^2/sec is given for different dates. Estimated value of percent polarization due to molecular emission is listed for some molecules. P_{max} values (theoretically calculated) are also given.

Date		CN 3871/50	C_3 4060/65	CO^+ 4260/65	C_2 5140/90	H_2O^+ 7000/175
Feb 20, 90	P_o				11·0	14·3
	E_P				1·4	2·1
	θ_o				35	24
	E_θ				4	4
	F_c				6·145E-12	7·955E-12
	F_E				1·177E-12	
	P_E				10·0 ± 3·0	
May 2, 90	P_o	6·25	3·46	7·18	6·47	14·56
	E_p	0·20	0·6	0·14	0·5	1·9
	θ_o	24	20	25	21	27
	F_θ	1	3	1	1	2
	F_c	1·063E-10	5·055E-10	2·117E-10	3·435E-10	1·068E-11
	F_E	1·909E-09	7·075E-10		3·953E-09	4·919E-11
	P_E	6·0 ± 0·2	1·0 ± 0·6		6·0 ± 0·5	0·4 ± 1·9
	P_{max}	7·0	1·1		6·8	0·5
May 4, 90	P_o	5·95	2·75		6·41	13·77
	E_p	0·40	0·50		0·17	1·10
	θ_o	18	17		16	16
	E_θ	2	5		1	2
	F_c	1·005E-11	4·770E-10	1·993E-10	3·417E-10	1·545E-10
	F_E	1·628E-09	1·545E-09		2·474E-09	6·542E-11
	P_E	6·3 ± 0·6	2·6 ± 0·6		6·1 ± 0·3	1·1 ± 1·8
	P_{max}	6·8	2·9		6·7	1·2

the blue continuum filter which has a small contamination due to C_2 molecular emission. The blue continuum band (effective wave length: 4845 and half width: 65A) falls between the two C_2 bands at 4745A and 5165A. The effect of the tail of C_2 emission band starting at 5165A, on the continuum band at 4845A is of the order of 1%. The expression for estimating the corrected magnitude at λ=4845A is:

$$CM = m(4845) - 0.012\{m(5150) - m(4845)\} \tag{2}$$

where CM is corrected magnitude (refer IHW Photometry and Polarimetry Net circular No. 3, February 1986). Thus the total error, in flux measurement of the blue continuum, including the error in observed magnitude, is 7% and in other two continuum bands, which are nearly free of molecular emission, the error is 5%. The continuum flux at the molecular emission bands has been calculated using the expressions given in the IHW Photometry and Polarimetry Net, Circular 3,1986. The estimated error in flux in molecular bands is ~ 9%. For all practical purpose, we have considered the error in flux to be less than 10% in all the bands.

On February 20, the comet was very low at the time of observation (about 15 degrees above the horizon). The error in magnitudes due to errors in extinction and transformation to standard magnitude is found to be 0.15 mag. There are some other sources of error as discussed above. The total error in flux in continuum bands (BC and RC) and molecular bands (C_2 and H_2O^+) is evaluated to be 20%.

4. Results and discussions

In the following we discuss the results on: (i) continuum energy distribution and polarization, (ii) molecular band emission and (iii) molecular band polarization.

4.1 *Continuum Energy Distribution and Polarization*

Table 1 lists the observed magnitudes and polarization values in the IHW filter system for comet Austin on February 20, May 2 and May 4, 1990. The error in polarization measurement is also given. Fluxes in three continuum filters have been calculated as discussed above and are given in Table 1. In Fig. 1, we have plotted the observed flux in the continuum bands normalized by a solar analog HD 191854 on May 2 and May 4. We have not plotted in Fig. 1 the flux values on February 20 since observations could not be made through the UC band and because the errors in observations in the other two continuum bands (BC and RC) are large (20%). Fig. 1 shows that on May 2 and May 4 the comet is bluer than the Sun. The error in flux measurement on May 2 and May 4 is less than 10% and the observed bluing is much higher (refer Fig. 1). The bluer color than a solar analog is not a common feature in comets; although bluing has been observed in the case of comet Ikeya-Seki (1967n) (Gebel 1970).

Figure 2a shows the wavelength dependence of the degree of polarization. There is a sharp increase in the degree of polarization towards the red wavelength in post-perihelion phase. Observations obtained on February 20 also show increase in the degree of polarization towards the red wavelength, though the rate of increase is

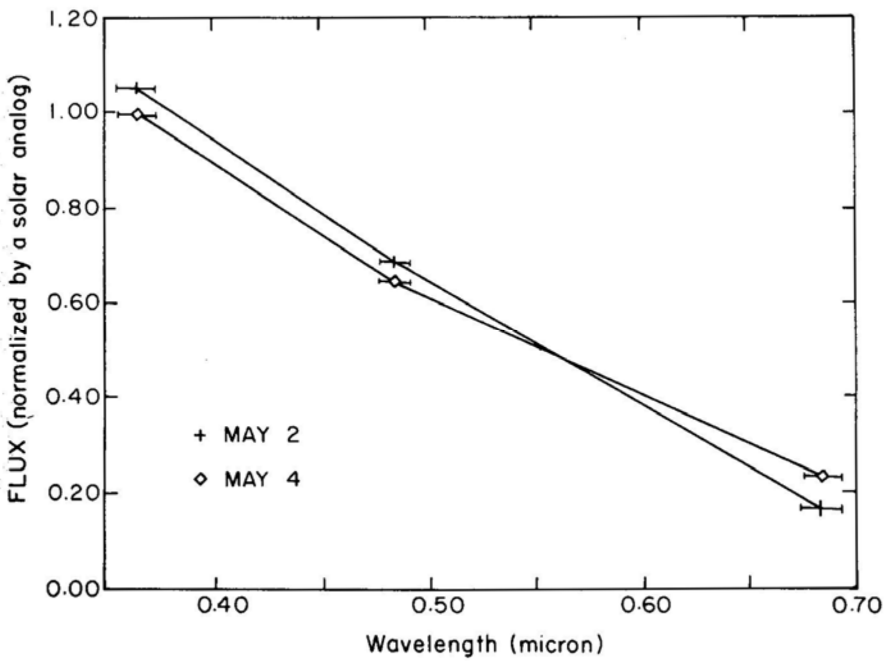

Figure 1. Plot of flux values (in unit of 10^{-12} ergs/cm^2/sec/A), normalized with respect to a solar analog HD 191854, in different continuum bands for comet Austin on May 2 and May 4.

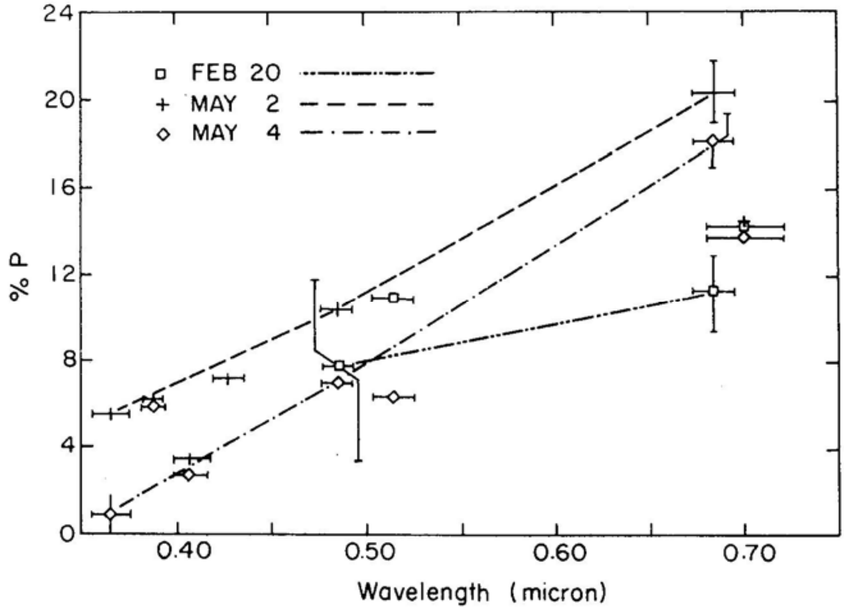

Figure 2a. Wavelength dependence of linear polarization for comet Austin as measured on different dates. Polarization values for continuum wavelengths are joined with different types of dashing. Observed values of polarization for molecular bands are also plotted for comparison. Error bars (two sigma) are also plotted.

relatively less compared to that on May 2 and May 4. The maximum polarization, P_{max} (polarization value at phase angle 90 degree) is related to the albedo A of the surface, by the classical so-called Umov approximate relationship $P_{max} \cdot A$ = const. (Dollfus 1989). The present observations on comet Austin have been made on May 2 and 4 when the phase angle is 109 and 107.4 degree respectively. Assuming that the observed polarization on May 2 and 4 is close to P_{max} (since the phase angle at the time of observation is not very much off from 90 degree), the above relation shows that for comet Austin the albedo in ultraviolet wavelength is 3 to 4 times higher than for the red wavelength which imply the brightness of comet Austin to be more in blue wavelength compared to that in red wavelength. This is consistent with the observations.

The steep rise of polarization towards longer wavelengths and bluing of the continuum flux in comet Austin indicate that the size of the dust particles in comet Austin lies in a narrow range and the imaginary part of the refractive index may be small i.e. close to zero (refer Greenberg 1978; Martin 1978). Comparison of the various curves for scattering efficiency and polarization due to dust particles, given by Greenberg (1978) and Martin (1978), with the present observations of flux and polarization help to put a limit on the sizes of the cometary dust particles; the sizes of the dominant dust particles appear to range between 0.1 μm to 0.5 μm. Calculations based on Mie scattering theory were carried out by us to match the observed polarization data in the B and R bands with the theoretical predictions and to find out the characteristics of the cometary dust. This analysis, published elsewhere (Sen *et al.* 1991) also shows that the relative abundance of smaller dust particles is more in comet Austin as compared to comet Halley and a large fraction of them are smaller than 0.62 μm.

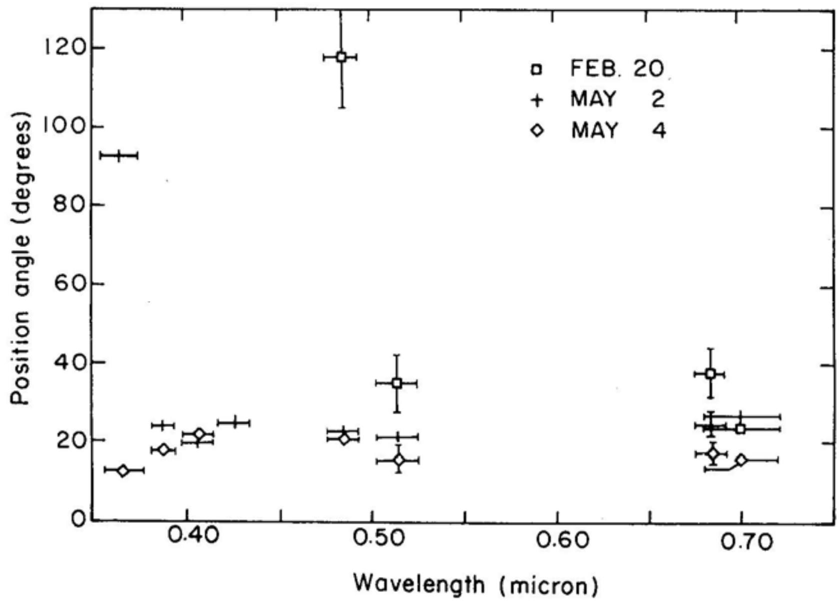

Figure 2b. Wavelength dependence of position angle as measured on different dates; error bars are plotted.

Figure 2b shows the wavelength dependence of position angle of the polarization. Within the errors of measurements, the polarization angle for continuum and molecular bands is constant (except for BC on February 20 and for UC on May 2) and is found to be perpendicular to the scattering plane. During pre-perihelion phase on February 20, the BC shows a flip of about 80 degrees in the position angle. Since observations could not be made on February 20 in other shorter wavelengths due to low flux level and high atmospheric attenuation as the comet was very low at the time of observations, it is difficult to infer whether the flip in position angle observed in BC extends to other shorter wavelengths. A flip of 90 degrees is possible for shorter wavelengths which again depends on the Sun-comet-Earth phase angle and characteristics of dust particles. The error in polarization measurement in BC on February 20 is large (refer Table 1) and expected error (one sigma) in position angle is also large ($E_\theta \sim 14$ degrees). Therefore, it is difficult to say whether the flip in position angle observed in BC corresponds to a 90 degree flip. The flip observed in UC on May 2 appears genuine as the error in polarization measurements are very low (refer Table 1). In general the flip in polarization angle has been noticed in most of the comets at low phase angle (phase angle < 22 degree) (Dollfus 1989). Weinberg & Beeson (1975, 1976) have made extensive polarization measurements on Ikeya-Seki (1965 VIII) for different scattering angles. The most interesting result of their observations is the change in polarization from positive to negative values for λ=0.53 μm as the scattering angle changes from 116 to 135 degrees. Polarization reversal is present in planetary atmospheres including the Earth's atmosphere and has been found in zodiacal light also (Wolstencroft & Rose 1967; Weinberg & Mann 1968; Frey *et al.* 1974). Of particular interest in the zodiacal light is the possibility of positive and negative polarization at small elongation in the vicinity of 0.43 μm (Weinberg & Mann 1968). The steep change in the degree of polarization and the large amount of negative polarization are characteristics of a narrow range of small particles having a small imaginary part in their refractive index which is again consistent with the inference made earlier on the basis of continuum flux distribution and the wavelength dependence of the polarization.

The polarization reversal may arise as a result of (i) the segregation of different size grains in the tail of the comet due to the effect of radiation pressure; (ii) alignment of the non spherical grains in the cometary atmosphere (Swamy 1978; Kiselev & Chernova 1981). The second mechanism does not seem to fit the present observations of May 2 as both the positive and negative polarizations are present at different wavelengths. Segregation of the grains in the tail is one possibility or that comet Austin has a narrow range (0.1 to 0.5 μm) in the dust distribution in reality. Due to projection effects radiation from a larger area of the comet is reaching us on May 2 (phase angle 109.0 degree) as compared with May 4 (phase angle 107.4 degree). Therefore, segregation of the grains cannot be ruled out.

4.2 *Molecular Band Emission*

Flux in the emission bands of CN, C_3, CO^+, C_2, H_2O^+ are given along with the background solar continuum flux in Table 2. The data in Table 2 show that C_2 is always strongest whether it is pre- or post-perihelion phase. A similar trend has been observed in the case of comet Halley (Sen *et al.* 1989). The flux in C_3 relative to C_2 shows significant variation between May 2 and May 4. Regarding the emission from the ionic molecules: H_2O^+ is quite weak whereas CO^+ could not be detected. H_2O^+ has not been detected in our observation on February 20 (pre-perihelion time), while the observations made in the post-perihelion phase show the presence of ionic water molecule; the flux value shows an increase of about 30% on May 4 as compared to the flux on May 2. The increase in H_2O^+ flux is three times the estimated error and, therefore, it is significant. In comet Austin CO^+ is perhaps below our detection limit (lower than 1.0E-11 ergs/cm^2/sec) on all the observing dates; this molecule was found present in comet Halley on March 19, 1986 (Sen *et al.* 1989).

The present observations show that there is some correlation among the molecular emissions from the molecules: C_2, C_3, CN and H_2O^+. C_3 emission shows an enhancement (on absolute term) on May 4 by a factor of 2 as compared to the emission on May 2 and at the same time H_2O^+ is enhanced by about 30%. If we look at the emission flux from CN and C_2 on May 2 and 4, we find an anti-correlation with C_3 emission; C_3 emission decreases with the enhancement of CN and C_2 (refer Table 2). There are some ideas published in the literature on the production mechanism of C_3 molecule (Stief 1972) though the scenario is not clear. The present observations indicate that the enhancement of H_2O^+ is related with the enhancement of C_3. Perhaps one may explain the above observations as follows:

It is believed that most of the H_2O^+ is produced during an eruption. The higher mobility of the ionic water molecules causes them to travel farther out than the neutral molecules and can produce a halo around the comet nucleus which may prevent UV radiation from the Sun reaching inside the halo. This will reduce the dissociation rate of C_3 molecule and enhance C_3 emission. The possibility of sudden enhanced formation of C_3 molecule by chemical combination of some other carbon containing molecules, released during eruption, cannot be ruled out. The formation mechanism of C_3 molecule is not well understood at present and its parent molecule is not known definitively.

4.3 *Molecular Band Polarization*

The observed degree of polarization and position angle in continuum filters and in the molecular bands are listed in Table 1. Flux in different emission bands are given along with the background continuum in Table 2. The polarization observations show that the polarization vector in the emission and continuum is in the same direction i.e. perpendicular to the scattering plane. The exception to this are the polarization vector in the B and U bands as observed on February 20 and May 2 respectively. However, the observed polarization vector for molecular bands redwards of the B-band on February 20 and of the U-band on May 2 are nearly perpendicular to the scattering plane. This means that the polarization vector due to the background continuum at the molecular band emission is also perpendicular to the scattering plane. This situation simplifies the procedure of separating the polarized flux due to the fluorescence emission from the observed molecular band polarization. In such a case the observed polarization flux in a molecular band is the scalar sum of emission and continuum polarization flux which can be expressed as:

$$P_o \cdot F_{\text{Tot}} = P_E \cdot F_E + P_c \cdot F_c \qquad (3)$$

where P_o is the observed degree of polarization and P_E and P_c are respectively the degree of polarization due to the molecular emission and continuum; F_{Tot} is the total flux and F_E and F_c are respectively the flux due to molecular emission and the continuum. In different emission bands, the contribution to the degree of polarization due to the background continuum has been found by interpolating the flux values between continuum values (using Fig. 2a). The continuum polarization at the position of molecular bands thus found is used to calculate the value of P_E using relation (3). The values of P_E are listed in Table 2.

The molecular band polarization values (Table 2) for C_2, C_3 , CN and H_2O^+ molecules measured on May 2 are close (within the error bars) to the values obtained on May 4. This is expected as the phase angle has not changed much during the observing run in May (phase angle at the time of observation on May 2 and 4 was respectively 109.0 and 107.4 degrees). We have theoretically calculated P_{max} (maximum polarization at phase angle 90°) as discussed by Sen *et aL* (1989) and the values thus obtained for May 2 and 4 are listed in Table 2. We have not calculated the value of P_{max} for February 20 as the error in flux measurement is relatively large. From the theoretical calculations by Ohman (1941) a value of 7.7% for P_{max} is expected for CN and C_2 molecules. The P_{max} values obtained for CN and C_2 in the present work are in agreement (within the error bar) with the theoretically expected values. The estimated value of C_3 band polarization on May 2 and 4 matches within the error bars. However, the P_{max} value (Table 2) is much below the theoretically expected value. In the case of comet Halley also (Sen *et al.* 1989) the polarization value was found to fall much below the theoretically predicted value based on the theoretical relation given by Ohman (1941). At present we have no satisfactory explanation.

The mean value of P_{max} for H_2O^+ emission in comet Austin on May 2 and May 4 is: P_{H_2O}~ 0.8 ± 1.4% (refer Table 2). In case of comet Halley the estimated polarization value of H_2O^+ is quite large (P_{H_2O+} ~ 29%) (Sen *et al.* 1989). However, in case of Halley the error was large (comparable to the observed polarization value) and therefore the estimated value of polarization for H_2O^+ molecule in Halley should be taken cautiously. The main reason for large errors in p/Halley is very low flux level for the ionic water molecule. In case of comet Austin the polarization of ionic water molecules has been found to be low. Future Polarimetric observations on ionic molecules in bright comets will be useful.

5. Conclusions

1 The flux distribution of comet Austin as observed through the three IAU/IHW continuum filters is bluer on May 2 and 4 compared with the solar flux distribution.
2 Wavelength dependence of polarization in comet Austin on May 2 and 4 shows that the polarization decreases sharply with decreasing wavelength. Polarization vectors in continuum and emission bands are perpendicular to the scattering plane. However, some measurements deviate significantly from it.
3. The steep wavelength dependence of the degree of polarization and the bluer flux distribution compared to a solar analog indicate that the dust size distribution lies in a narrow range and the sizes of the dominant particles are expected in the range of 0.1 μm to 0.5 μm.
4. Neutral molecular bands: C_2, CN and C_3 are strong. The flux values for C_3 molecule show (Table 2) significant variation on different dates; H_2O^+ was present on May 2 and 4 (post-perihelion phase).

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