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RESEARCH ARTICLE

Molecular band polarization in Comet Hyakutake C/1996 B2

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IAU/IHW filter set is used to study the polarization in Comet Hyakutake in various molecular bands. The observations were taken on March 13.97 and March 18.88 UT dates using 1.2 m telescope at Mount Abu Observatory, India. The errors in the measurement of the percent polarization are very low (<0.5%). The phase dependence of the polarization of C_2 and CN molecular emission bands due to resonance fluorescence is in good agreement with theory. However, the observed polarization in C_3 molecular band is found to be about 3% which is less than the predicted value. In the case of CN molecule, significant deviation is noticed in the direction of polarization vector from normal to the plane of scattering.

COMETARY polarimetry provides a very good technique to understand the properties of gas molecules and dust. The level of polarization is strongly correlated with the activity of nucleus and the presence of jets which exhibit increased polarization over the surrounding coma. The mechanisms for the cometary polarization are now known to be: (i) scattering of sunlight by the cometary particles, and (ii) the resonance fluorescence emission by the cometary molecules. However, the molecular band polarization in visible spectral range has not been explored much, neither observationally nor theoretically. The theory of polarization of molecular bands was studied a long time ago by Mrozowski[1], though this work does not deal with molecular bands observed in comets. Since then there seems to be no theoretical work done on this subject. As far as observations are concerned, Ohman[2,3] showed for the first time the presence of polarization in comets due to resonance fluorescence emission. Further works are by Blackwell and Willstrop[4], Bappu *et al.*[5], Kharitonov and Rebristyi[6], Le Borgne *et al.*[7], Sen *et al.*[8] and Joshi *et al.*[9], where they have made measurements for comets P/Halley, Hartley-Good, and Austin in molecular bands, OH (3090 Å), CN (3871 Å), C_2 (5140 Å), etc. In most of the cases earlier to 1987 it is not clear whether continuum light was subtracted correctly from the measurements. In case of Comet P/Halley's recent apparition, IHW group provided similar IAU/IHW filter set to several groups and therefore it was possible to generate homogeneous data base for this comet. Subsequently, we made use of the same filter set in case of Comet Austin and now on Comet Hyakutake C/1996 B2, making it possible to compare the results on different comets.

Here we report the linear polarization measurements in some molecular bands in Comet Hyakutake C/1996 B2.

Observations and analysis

Observations were made with a photopolarimeter on the 1.2 m telescope at Gurushikhar (longitude = 72°46' 47.47"E; latitude = 24°39' 8.84"N; height = 1680 m above sea level) near Mount Abu, operated by Physical Research Laboratory, Ahmedabad. The PRL photopolarimeter fitted with IAU/IHW filter set was mounted at the Cassegrain plane. The polarimeter works on the principle of rapid modulation of incoming light by a fast rotating superachromatic (in 0.3 μm to 1 μm spectral region) Pancharatnam half wave plate[10]. The details of the polarimeter used are given elsewhere[11]. The comet observations were made, with an aperture of 26.5 arcsec centered on the nucleus, on March 13.97 and March 18.88 UT decimal dates. The IAU/IHW filter set, used for observations, contains three continuum bands, 3650/80, 4845/65 and 6840/90 free from any cometary emission, and five molecular emission bands, CN (3871/50), C_3 (4060/70), CO^+ (4260/65), C_2 (5140/90) and H_2O^+ (7000/175) (all figures are in Angstrom, central wavelength/band pass). The solar type stars HD105590 and HD191854 were observed for photometric calibration. The entire photometric procedure including the measurement of flux values in different emission bands is described by Ganesh *et al.*[12] (Paper I). The details of the polarimetric analysis procedure are discussed by Joshi *et al.*[13] (Paper II) who report the continuum polarization behaviour of the comet on the two dates.

In the emission bands, the observed flux is equal to the sum of the flux due to reflected solar continuum (F_C) and the flux due to the fluorescence emission from gas molecule (F_E). The contribution of emission polarization to the observed polarization can be found out with the help of Stokes parameters: $Q = FP\cos 2\theta$ and $U = FP\sin 2\theta$, where P is the degree of polarization, θ is position angle and F is the flux. The observed values of polarization P_{obs} and position angle θ_{obs} in emission bands are due to the mixing of emission light with continuum. Using Stokes parameters Q and U, one can estimate the emission polarization P_E and θ_E. We can write: $Q_{obs} = Q_E + Q_C$ and $U_{obs} = U_E + U_C$, where the subscript E and C stand for emission and continuum respectively. We write the final equations in the form,

$$P_{obs}F_{obs}\cos 2\theta_{obs} = P_E F_E \cos 2\theta_E + P_C F_C \cos 2\theta_C, \quad (1)$$

$$P_{obs}F_{obs}\sin 2\theta_{obs} = P_E F_E \sin 2\theta_E + P_C F_C \sin 2\theta_C, \quad (2)$$

where F_C and P_C are respectively the contribution of continuum flux in the emission band and the polarization due to this continuum.

The observed degrees of polarization in continuum and emission bands are listed in Table 1 and are plotted in Figure 1. The polarization due to continuum, P_C, in a particular emission band is estimated from Figure 1 by interpolation. The molecular band polarization P_E has been calculated using equations (1) and (2) and the values obtained are given in Table 2 along with various physical quantities needed in the calculation. The values of F_E and F_C are taken from Paper I. The value of F_{obs} is simply the sum of F_C and F_E. After inserting the known values of F_{obs}, F_C, F_E, P_{obs}, and P_C in equations (1) and (2), we get the values of $Q_E = P_E\cos 2\theta_E$ and $U_E = P_E\sin 2\theta$. The value of P_E is calculated from Q_E and U_E using the relation $P_E = \sqrt{(Q^2 + U^2)}$. The emission band polarization values thus obtained are listed in Table 2 and shown in Figure 2 in the form of bar diagram.

Results and discussion

The observed continuum polarization is very close to the theoretically-calculated polarization value taking grain characteristics similar to comet Halley (Paper II). In general, the polarization vector is expected to be normal to the scattering plane. However, the observed values (see Table 1) show a small deviation in the position angle in U-continuum and in CN band on March 13.97. The position angle in 3650 Å band on March 13.97 is 16 ± 2 degrees whereas in 4845 Å continuum band its value is 13 ±1 degrees. Within the errors both the values can be taken as same. However, on March 13.97, θ deviates by about 4 degrees in 3650 Å band compared to the value in 4845 Å band, which is more than three sigma and therefore can be taken as real. This small deviation may be attributed to several factors, some of which are described in Paper II.

The polarization vector for the molecular bands is perpendicular to the scattering plane within the error of observation (c.f. Table 1). The position angle in the CN band shows a significant deviation from the normal to the scattering plane on March 13.97. However, the observed molecular band polarization is contaminated by the continuum. It would be more interesting to study the polarization behaviour of pure molecular emission which is listed in Table 2. Before we discuss the polarization behaviour of molecular bands, it is appropriate to look for the error in estimating P_E.

If we assume that emission and continuum bands have the polarization vector in the same direction (i.e. perpendicular to the scattering plane), then,

$$P_E F_E = P_{obs}(F_C + F_E) - P_C F_C. \quad (3)$$

From the observed data we notice that the above assumption is quite reasonable. We also notice that the errors in polarization measurements are extremely low (S/N ratio being more than 10); the worst case being the

Table 1. Observed magnitudes and polarization data on Comet Hyakutake C/1996 B2 on two different dates. %P, E_P, θ, E_θ are respectively the observed degree of polarization (in %), percent error in polarization, position angle, error in position angle (degrees)

Waveband	UT decimal date March 13.97					UT decimal date March 18.88				
(Å)	$\%P_{obs}$	E_P	θ	E_θ	Mag.	$\%P_{obs}$	E_P	θ	E_θ	Mag.
3650*	6.38	0.50	16	2	10.30	4.98	0.31	4	2	9.65
3871 (CN)	3.65	0.49	21	3	9.24	4.58	0.31	8	2	8.69
4060 (C_3)	4.71	0.26	10	1	9.53	4.25	0.19	6	1	8.80
4260 (CO^+)	5.69	0.26	11	1	9.74	5.08	0.14	7	1	8.79
4845*	5.77	0.21	13	1	8.93	5.32	0.17	8	1	8.04
5140 (C_2)	4.84	0.19	12	1	8.49	4.52	0.13	7	1	7.86
6840*	6.32	0.29	14	1	7.90	6.26	0.24	7	1	7.46
7000 (H_2O^+)	6.47	0.25	14	1	7.82	5.74	0.15	5	1	7.04

*Continuum bands.

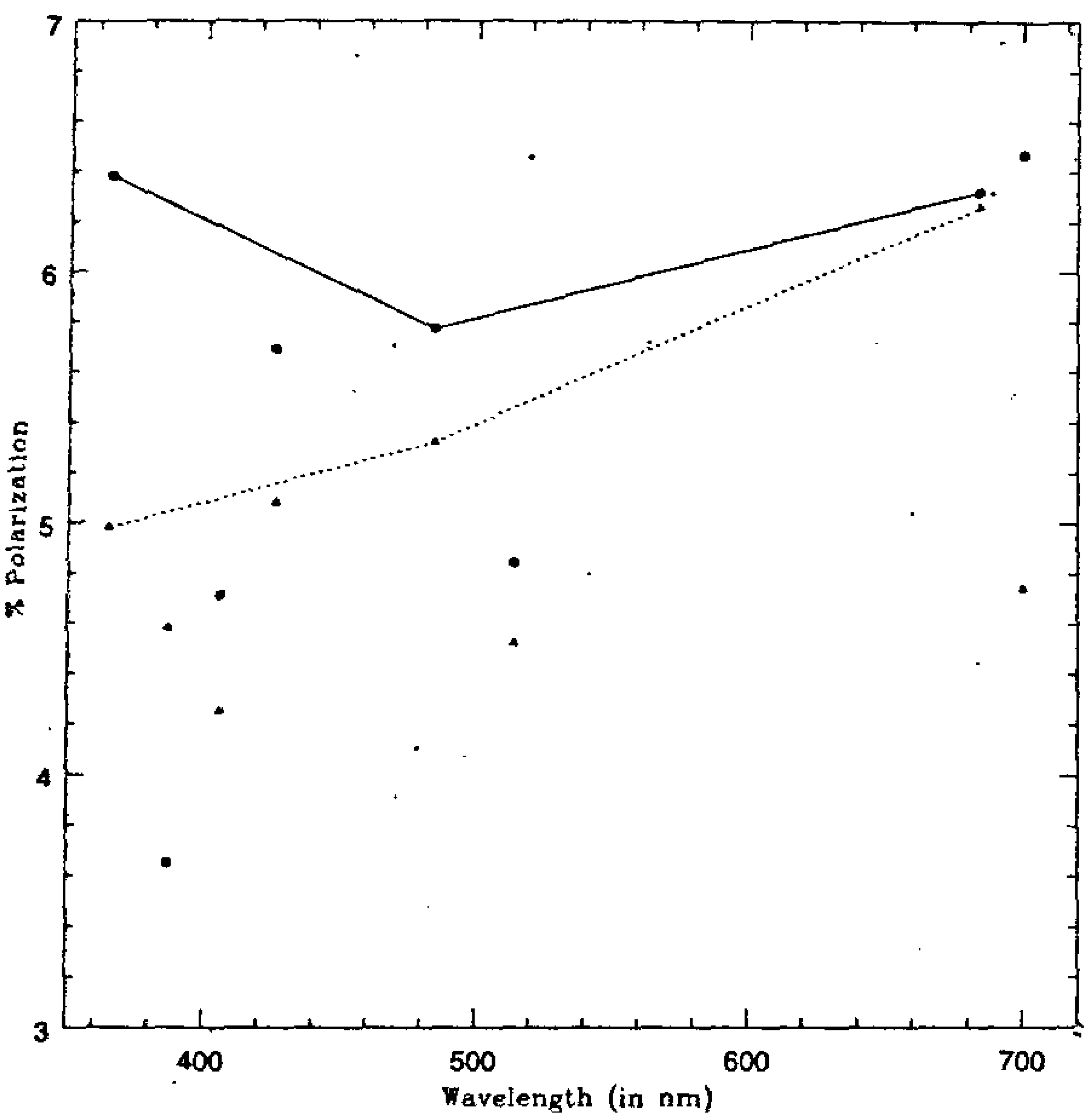

Figure 1. The observed continuum and molecular emission band polarizations plotted as a function of wavelength. The continuum points for March 13.97 and March 18.88 observations are joined by solid line and dotted line, respectively. The observed data are shown by filled circles and filled triangles for March 13.97 and 18.88 UT dates.

3650 Å band in which ε_P is ~0.5% (Table 1). The main source of error in the estimation of P_E is the error in flux measurements. The accuracy of flux measurement is estimated at a level of ~10%. Neglecting the error in polarization values, the expected error in molecular emission polarization can be written as

$$\delta P_E^2 = \left(\frac{\delta P_E}{\delta F_C}\right)^2 \delta F_C^2 + \left(\frac{\delta P_E}{\delta F_E}\right)^2 \delta F_E^2 . \quad (4)$$

The ratio $r = F_C/F_E$ plays an important role in error estimation. If r >> 1 (which is the case with CO^+ and H_2O^+) we can simply write,

Table 2. Values of the polarization for considered molecules in different wavebands

Waveband	M_C	F_C	F_E	P_C	P_E
		March 13.97			
3871 (CN)	10.5	9.23E-12	2.14E-11	6.38	2.48
4060 (C_3)	9.92	1.43E-11	6.02E-12	6.17	2.02
4260 (CO^+)	9.77	7.18E-11	1.58E-12	6.06	48.3
5148 (C_2)	8.88	1.95E-10	7.62E-11	5.79	2.47
7000 (H_2O^+)	7.86	2.56E-10	9.58E-12	6.41	20.04
		March 18.88			
3871 (CN)	9.84	1.75E-11	3.32E-11	5.03	4.41
4060 (C_3)	9.19	2.79E-11	1.18E-11	5.11	2.40
4260 (CO^+)	8.99	1.46E-10	3.04E-11	5.15	5.52
5140 (C_2)	8.02	4.19E-10	6.89E-11	5.37	1.30
7000 (H_2O^+)	7.45	3.75E-10	1.71E-10	6.06	5.49

$$\delta P_E \sim r\,((P_{obs} - P_C)/F_E)\delta F_E. \quad (5)$$

Using the values from Table 2 we see that r is rather large for the ionic molecules CO^+ (~50) and H_2O^+ (~30) on March 13.97, and therefore the emission band polarization for ions derived by this method has large errors. Therefore, the values of P_E and θ_E for CO^+ and H_2O^+ molecules on March 13.97, as listed in Table 2, may contain large errors and should be taken with caution. The CO^+ shows very high polarization value (48%). In case of Comet Halley also, CO^+ showed large polarization[8], though in that case also the errors were large. However, for other molecules the value of r is about 1 and therefore δP_E is small.

The value of P_E for CN, C_2 and C_3 molecules is estimated to be less than 3% on March 13.97. However, on March 18.88 polarization values for CN, C_3 and C_2 molecules are 4.41, 2.40 and 1.30, respectively. Thus neutral CN molecule shows higher polarization (4.58%) than one would expect from theory as discussed later but the value of P_E for C_2 band comes out to be lower than expected. This could be due to the overestimation of continuum polarization flux. Since the error in the de-

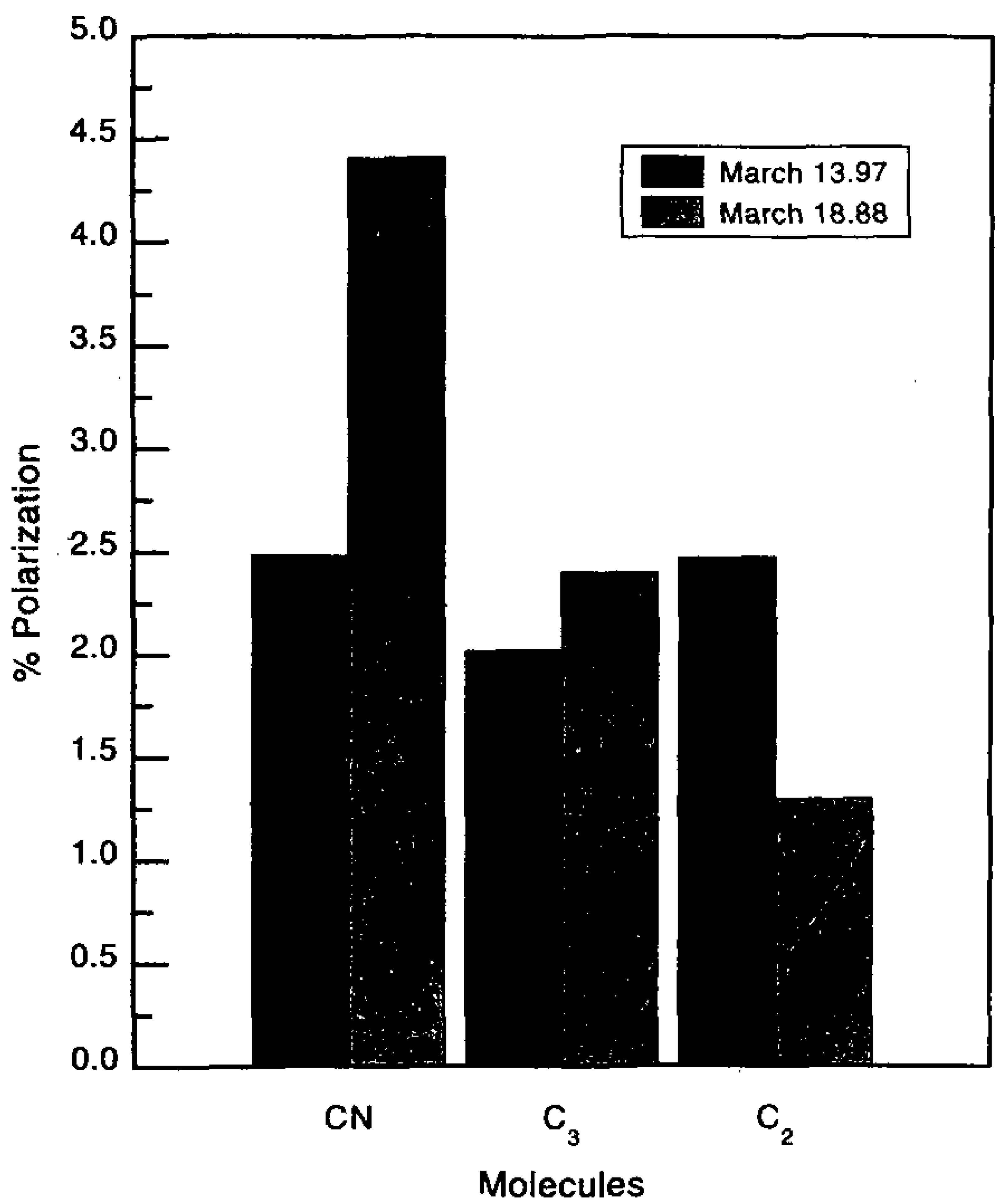

Figure 2. Bar chart showing a comparison of emission band polarization for CN, C_3 and C_2 molecules on March 13.97 and March 18.88.

gree of polarization is very small (≈0.24%), the major source of error seems to be overestimation of the continuum flux at 5140 Å obtained using formulae given in IHW Circular 3 Feb. 1984 which are basically for solar type flux distributions. The energy distribution of the comet on March 18.88 is found to be reddened (Paper I) and also peaking near 4845 Å compared to the solar analog. In the interpolation formulae to estimate continuum flux at 5140 Å, more weight is given to continuum flux at 4845 Å. Therefore, the flux gets overestimated in this procedure and the angle is also found to be significantly deviated from the normal to scattering plane. On the other hand, we estimated flux by linear interpolation between 4845 and 6850 Å, which comes out to be $\approx 2.559 \times 10^{-10}$ in the 5140 Å band. Using this value of flux, we obtain polarization value as 4.5% and angle θ as 7°, which are closer to theoretical predictions. The actual value for the molecular polarization is expected to lie between 1.5 and 4.5%.

The molecular band polarization $P(\alpha)$ observed at a particular sun–comet–earth phase angle α, is supposed to follow the following theoretical relation[3],

$$P(\alpha) = \frac{P_{max} \sin^2 \alpha}{(1 + P_{max} \cos^2 \alpha)}, \quad (6)$$

where P_{max} is the maximum polarization observed at a phase angle 90°. At the time of our observations, the phase angles were 36.9° and 38.1° respectively on March 18 and March 13. Theoretical calculations carried out by Ohman[3] predicted a value of 7.7% for P_{max} for CN and C_2 molecules. Putting this value of P_{max} in the above relation, we get $P_\alpha \approx 2.7\%$ and 2.8% respectively for phase angles 36.9 and 38.1° for CN and C_2 molecules. Therefore, the observed values are in good agreement with the theoretically calculated values. The observed molecular band polarization values for C_3 are 2.02 and 2.40% on March 13.97 and 18.88, respectively which are less than theoretically predicted value of ~6% (P_{max} taken as 19%). Similar values of polarization for C_3 band have been reported for Comet Halley and Comet Austin[7–9].

Conclusions

In the present work we have reported molecular emission band polarization in Comet Hyakutake C/1996 B2. The observations were taken on two UT dates: March 13.97 and March 18.88 using IAU/IHW set of filters. The errors in the measurement of the percent polarization are very low (<0.5%). The values of the polarization obtained in the present work and those predicted theoretically are in fairly good agreement for CN and C_2 molecules. However, in case of C_3 molecule the measured polarization values do not agree with the theoretically predicted value of P_{max} = 19%.

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