SPECTROPHOTOMETRY OF COMET AUSTIN (1982g) DURING POST-PERIHELION PERIOD

P. S. GORAYA, B. S. RAUTELA, and B. B. SANWAL
Uttar Pradesh State Observatory, Manora Peak, Naini Tal, India

(Received 30 September, 1983)

Abstract. Spectrum scans have been obtained of the head of Comet Austin on six nights at heliocentric distances (r) from 0.70 to 0.87 AU. The useful spectral region is λλ330–750 nm. Strong emission features of CN (388 nm) and Swan band sequence of C_2 (474, 516, and 563 nm) were identified. Weak emission features of CH + C_2(436 nm), C_2(600 nm), CN(420 nm) and CH + C_3(405 nm) have also been found present. There is a change in the ratio of CN(388 nm) to C_2(516 nm) emission strength with increasing heliocentric distance. An estimate of the CN and C_2 abundances has been made and their production rates have been derived. The continuum of the comet is strongly reddened with reference to Sun. The continuum matches the scattered continuum of solar radiation according to λ^2 law (Mie scattering) closely.

1. Introduction

In order to properly understand the nuclear structure of comets, it will be necessary to explain, quantitatively, the evaporation processes leading to the production of radicals, that are observed in cometary comae. The abundances of molecules and their production rates help us to understand the nature of the nucleus. Ideally, the abundance and the production rate of a given type of cometary molecule can be derived from 'monochromatic' observations in the light of an emission band due to particular molecule under consideration. Besides; the colour of the continuum of the coma in the visible region is not still clear. The colour depends on the size and nature of the particles responsible for scattering and absorbing the continuum radiation from the comae of comets. Spectrophotometric observations of the coma of a comet provide an opportunity to study both; its continuum and emission spectrum. We have, therefore, carried out a continuous scanning on the emission features as well as the continuum in the spectrum of Comet Austin in the visible region.

The comet was also observed by McCracken and Brown (1982). The spectrograms of Comet Austin, obtained by them, on August 19.06 UT showed emissions by CN, C_2, C_3, CH, and [OI]. Also, they noticed a weak continuum. Their observations refer to near perihelion period. Later on they again obtained spectrograms on August 26.06 UT, and confirmed the earlier reported emissions. In addition, emissions at OH and NH were also observed from the head of the comet.

2. Observations

The comet was observed on six nights, (basic parameters are given in Table I) at heliocentric distances from 0.70 to 0.87 AU, with spectrum scanner, mounted at the Cassegrain

Earth, Moon, and Planets **30** (1984) 63–74. 0167–9295/84/0301–0063$01.80.

TABLE I

Basic data of Comet Austin (1982g)

Date September, 1982 (UT)	Δ (AU)	r (AU)	m_v	Radius of the circular region in sky at distance Δ (km) $\times 10^4$	Area of the sky at distance Δ admitted through diaphragm $(km^2) \times 10^8$
5.6	0.94	0.70	6.35	1.46	6.69
8.6	1.02	0.73	6.60	1.58	7.88
9.6	1.05	0.74	6.75	1.63	8.35
18.6	1.27	0.83	7.70	1.97	12.22
20.6	1.32	0.86	7.90	2.05	13.20
21.6	1.34	0.87	8.00	2.08	13.60

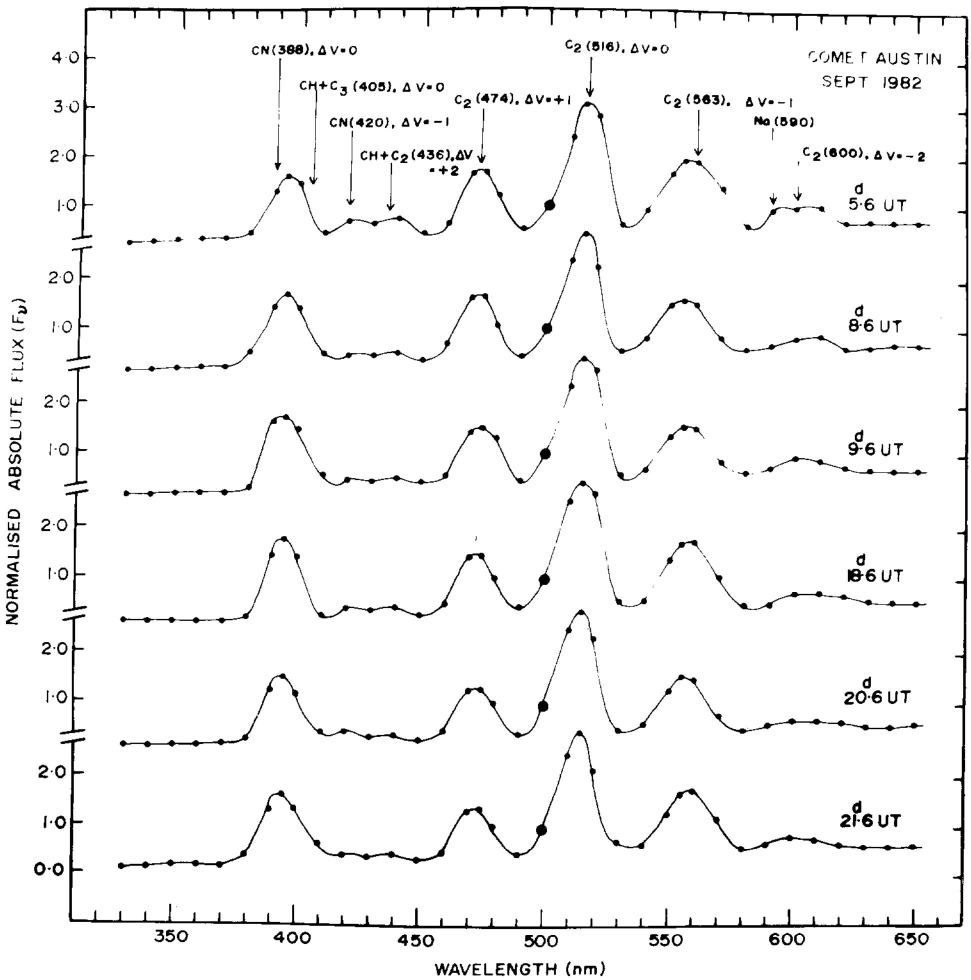

Fig. 1. Absolute flux distributions of the head of Comet Austin (1982g) on various dates, normalised to λ500 nm. The normalisation point is shown by a bigger dot.

focus ($f/13$) of the 104-cm reflector. The image has a scale of 15 arcsec mm^{-1} at the cassegrain focus of the reflector. A circular diaphragm of 3 mm corresponding to 45 arc sec as projected on the sky and centred on the nucleus was used. The exit slot of 50 Å band pass, in the first order, was used. The scanner consists of a Hilger and Watts monochromator giving a dispersion of 70 Å mm^{-1} in the first order. A cooled (– 20 °C)EMI 9658 B photomultiplier has been used as a detector and standard d.c. techniques were employed for recording. Scans of the neighbouring sky taken before and after each scan of the comet enabled elimination of the contribution by the background sky. During each night, about five to six scans of the comet were taken, out of which three or four good scans were averaged.

Along with the comet, the standard star α Lyr. was observed for calibration purpose. One late type star μ Her (G5IV) was also observed to serve as comparison star. The observations were corrected for atmospheric extinction and were reduced to absolute values. The absolute values of the fluxes thus obtained correspond to Tug *et al.* (1977) calibration of α Lyr. The absolute flux distributions of the comet, normalised to λ500 nm are shown in Figure 1. Since the observations were made near horizon, at large zenith angles, so the error due to large vaue of atmospheric extinction may be of the order of 0.20 mag. in absolute values.

3. Emission Bands and Flux Ratios

The spectra of the comet on various dates are plotted in Figure 1 to identify various spectral features. The spectral ragne is $\lambda\lambda$330–650 nm. Strong emission features of CN (388 nm) and Swan band sequence of C_2 (474, 516, and 563 nm) can easily be identified. The C_2 (516 nm) band sequence is the strongest in the whole spectrum. Because this system is very strong, its intensity is easily determined accurately and we have used it for normalisation. Emissions at C_2 (474 nm) and C_2 (563 nm) are of comparable strength. Beside these strong features, weak emission features of CH + C_3 (405 nm), CN (420 nm), CH + C_2 (430 nm) and C_2 (600 nm) are also present in the spectrum. Strong emission of CN (388 nm) was merged with weak emissions of CH + C_3 (405 nm). All these features are indicated by vertical arrows corresponding to the wavelength positions of each emission. Very weak trace of Na (590 nm) was found present only during first night on September 5. On other nights, Na was found absent. This agrees with the expected value of r for the disappearance of sodium emission (Bappu and Sivaraman, 1969). In order to measure fluxes in the emission bands, the continuum in the spectrum was located by selecting wavelength regions free of emission lines. The area of the strong emission bands was measured and converted into the total flux. The observed fluxes were reduced to a standard geocentric distance ($\Delta = 1.0$ AU), to study its variation with heliocentric distance (r). These reduced fluxes for strong bands of C_2 (474 nm), C_2 (516 nm), C_2 (563 nm), and CN (388 nm) are plotted in Figure 2. The intensities of the band sequences relative to that of C_2 (516 nm) are listed in Table II. The observed flux of the C_2 (516 nm) band sequence is given in the second column. The total luminosity (L) for C_2 (516 nm)

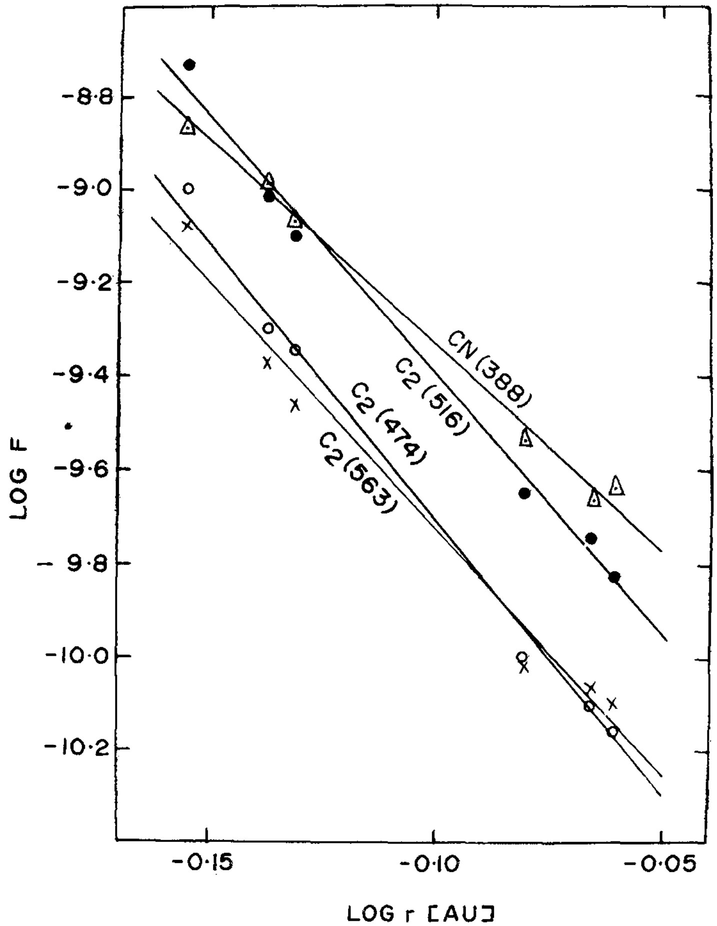

Fig. 2. The reduced flux of the CN and C_2 emission bands as a function of heliocentric distance. The straight lines have been fitted by eye.

band sequence is given in the last column of Table II. The emission band flux ratios are comparable to those obtained for Comet Kohoutek by Babu (1974), A'Hearns (1975), Sivaraman *et al.* (1979), and for Comet West by A'Hearn *et al.* (1980), for the same range of heliocentric distance. It is clear from Table II that the relative fluxes of C_2 (474 nm) and C_2 (563 nm) are constant, whereas that of CN (388 nm) increases as the heliocentric distance is increased. Many comets have shown this type of behaviour.

4. Abundances of CN and C_2 Molecules

The total number of molecules (N) of CN and C_2 contained in a cylinder of diameter 45 arc sec in the line of sight and extending through the comet, have been computed using the relation (cf. O'Dell and Osterbrock, 1962):

TABLE II

Emission band fluxes relative to C_2 (516), $\Delta V = 0$

Date September, 1982 (UT)	Apparent $F(C_2, \Delta V = 0)$ (erg cm^{-2} sec^{-1}) $\times 10^{-10}$	$F/F(C_2, \Delta V = 0)$					Luminosity L $4\pi\Delta^2 F(C_2, \Delta V = 0)$ (ergs sec^{-1}) $\times 10^{18}$
			C_2				
		CN ($\Delta V = 0$) (388 nm)	$\Delta V = +1$ (474 nm)	$\Delta V = 0$ (516 nm)	$\Delta V = -1$ (563 nm)	Continuum (530 nm)	
5.6	21.330	0.716	0.533	1.000	0.555	0.129	5.23
8.6	9.240	1.049	0.521	1.000	0.438	0.119	2.68
9.6	7.150	1.063	0.564	1.000	0.444	0.108	2.20
18.6	1.375	1.036	0.459	1.000	0.439	0.104	0.62
20.6	1.034	1.194	0.440	1.000	0.478	0.128	0.50
21.6	0.825	1.245	0.472	1.000	0.545	0.133	0.41

$$N = L \frac{m_e}{\pi e^2 f p \rho(\nu, r)},$$

where
L = the luminosity of respective band;
m_e = the mass of an electron;
e = the charge of an electron;
p = the vibrational transition probability;
f = the oscillator strength; and
$\rho(\nu, r)$ = the solar radiation density at frequency ν, at a heliocentric distance r.

The values of f, p, and $\rho(\nu, r)$ used in our calculations are those used earlier (Goraya *et al.*, 1982). Total number of molecules thus obtained are listed in Table III, along with the values of f, p, and $\rho(\nu, r)$.

TABLE III
Number of CN and C_2 molecules

Band	f	p	$\rho(\nu, r)$ (erg cm^{-3})	log N
CN ($\Delta V = 0$) 388 nm	0.0342	0.9200	$4.214 \times 10^{-20} r^{-2}$	30.28
C_2 ($\Delta V = +1$) 474 nm	0.0089	0.2409	$7.140 \times 10^{-20} r^{-2}$	30.80
C_2 ($\Delta V = 0$) 516 nm	0.0243	0.7335	$6.445 \times 10^{-20} r^{-2}$	30.30
C_2 ($\Delta V = -1$) 563 nm	0.0071	0.2142	$8.390 \times 10^{-20} r^{-2}$	30.56

5. Production Rates of CN and C_2 Molecules

In order to derive production rates, Q, of CN and C_2 molecules, we assume that the only excitation processes possible in the coma are those induced by solar radiation. Collisions within the coma and excitation by solar wind particles are neglected. For resonance scattering and resonance fluorescence, the luminosity is related to the total number of atoms or molecules, N, through the emission rate factor (Barth, 1969) g by .

$$L = gN$$

in terms of life time, τ, we have

$$Q = \frac{N}{\tau} = \frac{4\pi\Delta^2 F}{g\tau},$$

where
Δ = the comet–earth distance;
F = the observed flux from the comet;
τ = the life time of the scattering species; and
g = the probability that a solar photon will be resonantly scattered or produced by resonance fluorescence.

TABLE IV

Production rates of CN and C_2 molecules.

Date September, 1982 (UT)	log r (AU)	log Q (CN) (388 nm)	log Q (C_2) $\Delta V = +1$ (474 nm)	$\Delta V = 0$ (516 nm)	$\Delta V = -1$ (563 nm)
5.6	− 0.155	26.310	26.821	26.712	26.775
8.6	− 0.137	26.184	26.520	26.422	26.621
9.6	− 0.131	26.108	26.466	26.337	26.540
18.6	− 0.081	25.400	25.682	25.638	25.842
20.6	− 0.066	25.372	25.580	25.553	25.792
21.6	− 0.061	25.396	25.525	25.468	25.763

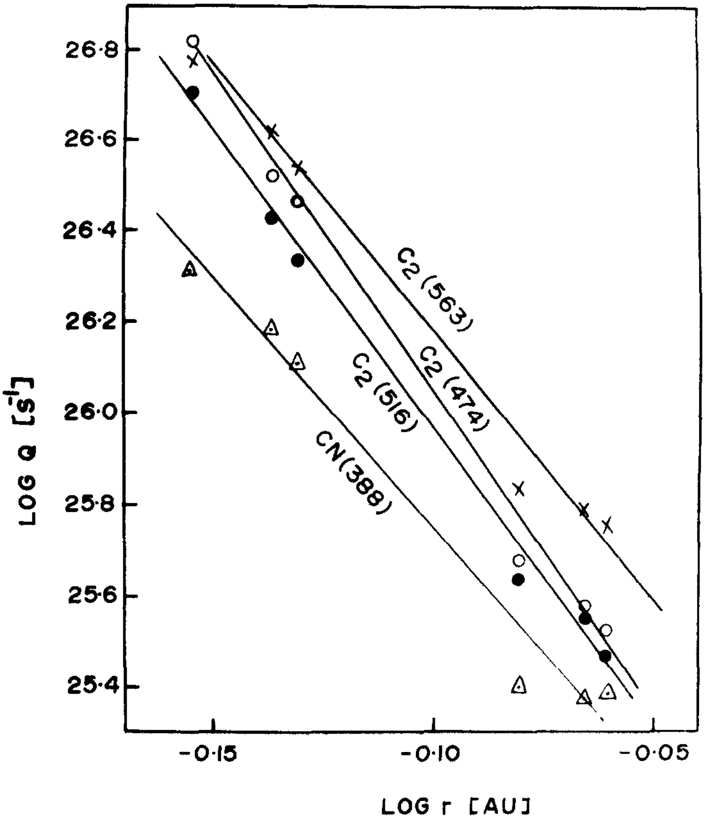

Fig. 3. The production rates of CN (388 nm) and C_2 (474, 516, and 563 nm) molecules as a function of heliocentric distance. The straight lines have been fitted by eye.

The values of τ used in our calculations are those obtained by Bappu *et al.* (1980), and of g-factors are those used by Newburn *et al.* (1978). The production rates of CN and C_2 molecules are listed in Table IV. The g-factors and life times may be uncertain by as much as ± 50%, producing the same order of uncertainty in production rates. The derived values of production rates are comparable with those of Comet Kohoutek (1973f), Comet Enke (1977XI), Comet Kohler (1977m) and Comet Bradfield (1979l) reported by A'Hearn and Millis (1980), during the same heliocentric distance range. The ratio of the production rate of CN to the production rate of C_2 (Q_{CN}/Q_{C_2}) is found to be equal to 0.45 ± 0.05, which is of the same order as given by A'Hearn *et al.* (1979) for Comets P/d'Arrest (1976e), P/Enke (1977), and P/Chernykh (1977l), in the same range of heliocentric distance. A plot of the variation of production rates of CN and C_2, with heliocentric distance is shown in Figure 3. A correlation between production rates of CN and C_2 is also shown in Figure 4. It is clear from Figure 4 that the points lie on a straight line, implying a constant ratio of production rates at different heliocentric distances.

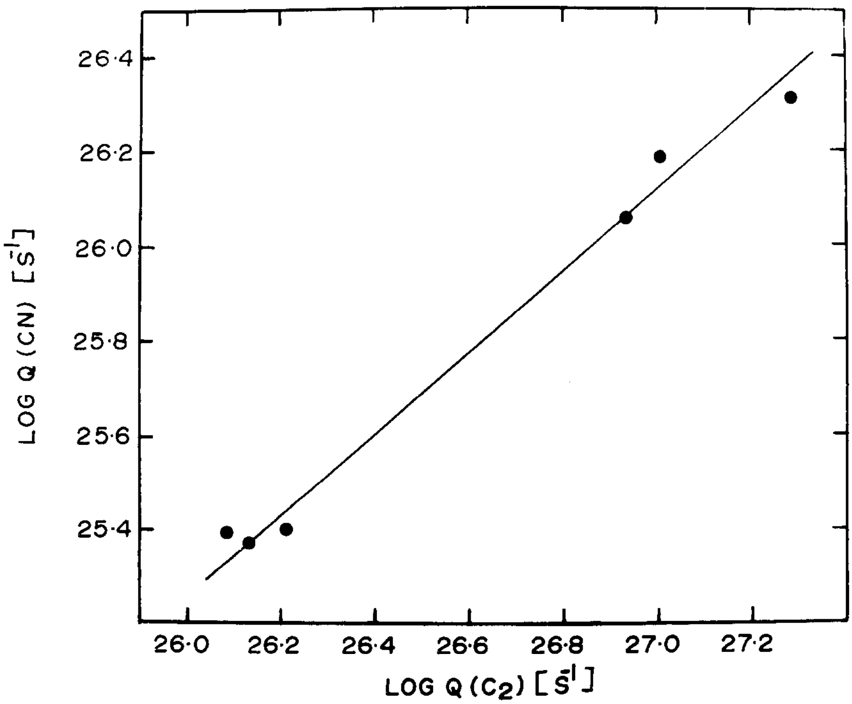

Fig. 4. Correlation between production rates of CN and C_2 molecules. The straight line has been fitted by eye.

6. Continuum Energy Distribution

Optical observations of the continuum radiation from comets can be used to infer the physical properties of solid particles. The wavelength dependence of the scattered light is an indicator of the size of the scattering particles.

The colour of the continuum radiation from the coma in the visible part of the spectrum is not clear. In previous studies, some comets were known to have had a pure reflection continuum; in the sense that the continuum spectra were unreddened with respect to that of the Sun (Arpigny, 1965; Gebel, 1970; Ney, 1974; Ney and Merrill, 1976; and Goraya *et al.*, 1982); whereas some others were found to produce continuum matching those of the late type stars around G8 (Walker, 1958; Bappu and Sinvhal, 1960; Vanýsek, 1960; Babu, 1974; and Kharitonov and Rebristyi, 1974). However, several spectrophotometric studies have indicated that the continuum is considerably reddened with respect to the Sun, (Chalonge and Bloch, 1966; Johnson *et al.*, 1971; Liller, 1960; Babu and Saxena, 1972; Stokes, 1972; Vanýsek, 1974; and Bappu *et al.*, 1980). The continuum was probably due to the scattering of sunlight by solid particles in the comae of those comets.

In an effort to study the continuum of Comet Austin in the present study, the continuum energy distributions have been obtained independently by taking the line-free regions and using α Lyr. as a standard star. The absolute magnitudes of continuum energy

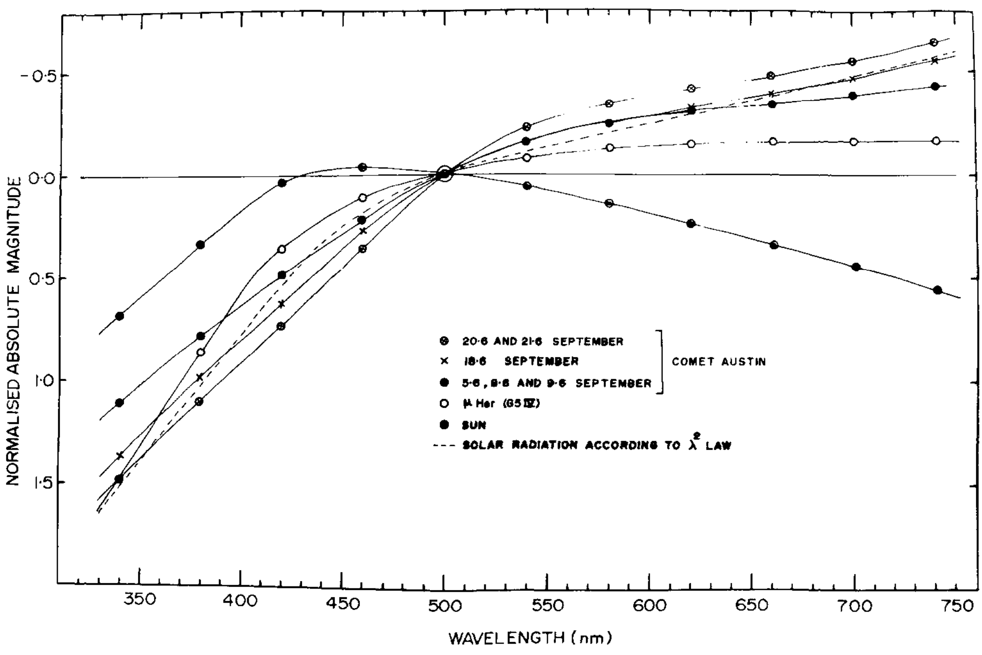

Fig. 5. Continuum energy distribution curves of Comet Austin, compared with those of μ Her, Sun and solar light scattered according to λ^2 law. All curves are normalised to λ500 nm and the Balmer discontinuity is smoothed out.

TABLE V

Absolute monochromatic magnitudes of Comet Austin, μ Her, Sun and solar light scattered according to λ^2 law, normalised to λ500 nm

Date September, 1982 (UT)	Wavelength (nm) 340	380	420	460	500	540	580	620	660	700	740	Name of the object
5.6, 8.6, 9.6 Mean values	+ 1.110	+ 0.780	+ 0.485	+ 0.220	0.000	− 0.155	− 0.235	− 0.300	− 0.335	− 0.385	− 0.425	Comet Austin (1982g)
18.6	+ 1.370	+ 0.985	+ 0.625	+ 0.275	0.000	− 0.155	− 0.235	− 0.315	− 0.385	− 0.470	− 0.550	Comet Austin (1982g)
20.6, 21.6 Mean values	+ 1.480	+ 1.095	+ 0.730	+ 0.355	0.000	− 0.220	− 0.330	− 0.405	− 0.470	− 0.550	− 0.640	Comet Austin (1982g)
	+ 1.480	+ 0.860	+ 0.360	+ 0.115	0.000	− 0.070	− 0.120	− 0.140	− 0.150	− 0.160	− 0.160	μ Her
	+ 0.685	+ 0.340	+ 0.040	− 0.035	0.000	+ 0.065	+ 0.145	+ 0.235	+ 0.340	+ 0.440	+ 0.555	Sun
	+ 1.520	+ 1.020	+ 0.530	+ 0.190	0.000	− 0.100	− 0.195	− 0.280	− 0.375	− 0.470	− 0.565	Solar light scattered according to λ^2 law.

distributions normalized to wavelength λ500 nm are given in Table V. A plot of these is shown in Figure 5, together with those of Sun and the solar light scattered according to λ^2 law (Mie scattering). The energy curve of a late type star μ Her (G5IV) has also been plotted in the same figure for comparison. It is clear from the figure that the continuum of the comet deviate strongly from that of the Sun; in the sense that comet continuum is reddened strongly as compared to that of Sun. The curve of the solar light scattered according to λ^2 law matches very closely with that of the comet.

The most interesting feature to be noted from comet energy distribution curves, is that they show an increase in reddening with increasing values of heliocentric distance. Many cometary continuum had shown this type of variation (Babu and Saxena, 1972; Vanýsek, 1974; Sivaraman *et al.*, 1979; and Bappu *et al.*, 1980). The increase in reddening with distance from the Sun can be explained in terms of typical particle sizes. Since our continuum measurements, which show this characteristic, can at best be interpreted in terms of the optical scattering; we hope that the continuum may be due to the scattering of sunlight by icy particles with rough and porous surfaces of diameters of the order of 0.25 to 5 μ. When such is the case, the scattering coefficient will be proportional to λ^2, so that the continuum will follow the λ^2 curve.

Acknowledgements

The authors are thankful to Dr S. C. Joshi for his kindness in going through the manuscript. Our thanks are also due to Dr K. S. Krishna Swamy for valuable discussions and suggestions, during the course of this work.

References

Arpigny, C.: 1965, 'A Study of Molecular and Physical Processes in Comets', Mem. Acad. Roy. Belgique, Cl. Sci. (8°) **35**, fasc. 5, p. 129.
A'Hearn, M. F.: 1975, *Astron. J.* **80**, 861.
A'Hearn, M. F., Hanisch, R. J., and Thurber, C. H.: 1980, *Astron. J.* **85**, 74.
A'Hearn, M. F. and Millis, R. L.: 1980, *Astron. J.* **85**, 1528.
A'Hearn, M. F., Millis, R. L., and Birch, P. V.: 1979, *Astron. J.* **84**, 570.
Babu, G. S. D.: 1974, 'The Study of Comets', in Donn *et al.* (eds.), *Proc. IAU Coll.* No. 25. p. 220.
Babu, G. S. D. and Saxena, P. P.: 1972, *Bull. Astron. Inst. Czech.* **23**, 348.
Bappu, M. K. V., Parthasarathy, M., Sivaraman, K. R., and Babu, G. S. D.: 1980, *Monthly Notices Roy. Astron. Soc.* **192**, 641.
Bappu, M. K. V. and Sinvhal, S. D.: 1960, *Monthly Notices Roy. Astron. Soc.* **120**, 152.
Bappu, M. K. V. and Sivaraman, K. R.: 1969, *Solar Phys.* **10**, 496.
Barth, C. A.: 1969, *Appl. Opt.* **8**, 1295.
Chalonge, D. and Bloch, M.: 1966, Liège Coll., 8°, No. 516, p. 281.
Gebel, W. L.: 1970, *Astrophys. J.* **161**, 765.
Goraya, P. S., Sinha, B. K., Chaubey, U. S., and Sanwal, B. B.: 1982, *The Moon and the Planets* **26**, 3.
Johnson, T. V., Lebofsky, L. A., and McCord, T. B.: 1971, *Publ. Astron. Soc. Pacific.* **83**, 93.
Kharitonov, A. V. and Rebristyi, V. T.: 1974, *Sov. Astron.* **17**, 672.
Liller, W.: 1960, *Astrophys. J.* **132**, 867.
McCracken, C. W. and Brown, L. W.: 1982, *IAU Cir.* No. 3722 & 3723.

Newburn, R. L., J. R. and Johnson, T. V.: 1978, *Icarus* **35**, 360.
Ney, E. P.: 1974, 'The Study of Comets', in B. Donn *et al.* (eds.), *Proc. IAU Coll.* No. 25, p. 334.
Ney, E. P. and Merrill, K. M.: 1976, *Science* **194**, 1051.
O'Dell, C. R. and Osterbrock, D. E.: 1962, *Astrophys. J.* **136**, 559.
Sivaraman, K. R., Babu, G. S. D., Bappu, M. K. V., and Parthasarathy, M.: 1979, *Monthly Notices Roy. Astron. Soc.* **189**, 897.
Stokes, G. M.: 1972, *Astrophys. J.* **177**, 829.
Tug, H., White, N. M., and Lockwood, G. W.: 1977, *Astron. Astrophys.* **61**, 679.
Vanýsek, V.: 1960, *Bull. Astron. Inst. Czech.* **11**, 215.
Vanýsek, V.: 1974, 'The Study of Comets', in B. Donn *et al.* (eds.), *Proc. IAU Coll.* No. 25, p. 1.
Walker, M. F.: 1958, *Publ. Astron. Soc. Pacific* **70**, 191.