Kodaikanal Obs. Bull. (1988) 10, 43-54

Polarimetry of supernova SN1987A - a dust shell model

U.C.Joshi, A.K.Sen, M.R.Deshpande and Rekha Jain
Physical Research Laboratory
Ahmedabad 380 009, INDIA

Summary

Polarimetric measurements of SN1987A in BVR bands were made on March 6 and 7. These observations along with the polarimetric data reported by various other authors within first 30 days of explosion have been discussed. There are atleast two intrinsic sources which contribute to the observed polarization; one source being the dust shell around SN1987A as is indicated by the wavelength dependence of linear and circular polarization and the other being due to the non-thermal synchrotron radiation from the exploding star itself. A dust shell model to explain polarization observations has been suggested. From the time variation of the wavelength dependence of linear polarization, the optical depth is found to be about 0.6, the radius of the dust shell about 0.04 pc and the grain size to be smaller than the interstellar grain size. The temperature of the dust shell is expected to be around 200 K. Based on this dust shell model, infrared excess beyond 10 micron has been found to be in agreement with the observed values.

Key words: Polarization-circumstellar dust-infrared radiation-supernova

1. Introduction

The polarization measurements of SN1987A through broad band filters were made to investigate the intrinsic polarization and its time variations. Earlier Schwarz and Mundt (1987) have reported polarimetry obtained on March 6 and 7 using several narrow-band and broad-band filters. Several other authors (Croper et al., 1987; Barrett, 1987a, 1987b; Bailey, 1987; Benvenuto et al., 1987) have reported polarimetric measurements. The observed degree of polarization is generally less than 1%. Barrett (1987a) has reported p=0.97% and θ=35.9 degree for a comparison star and has suggested the above value of polarization due to the interstellar medium. Schwarz and Mundt (1987) considered the above polarization value as interstellar polarization and have applied the same to correct the polarimetric data of SN1987A for interstellar polarization. However, Barrett (1987b) noted some change in the degree of polarization of the comparison star in his later observation. It is rather difficult to correct the observed data for interstellar polarization. However, good polarimetric data is available on SN1987A during the first one month time after the detection of the supernova in LMC. Photometric data in near infrared is also available (Bailey et al., 1987; Malkan and Sun, 1987; Bouchet et al. 1987) within the first 30 days. We have presented here discussions and analysis based on polarimetric data obtained by us on March 6 and 7 and by other investigators within one month (Table 1). Dwek et al. (1983) and Dwek (1983) have given models for a dust shell around the supernovae SN1979c and 1980k. A similar dust shell seems to explain the polarimetric observations of SN1987A. We have discussed and given a dust shell model for SN1987A which explains the polarimetric behaviour in optical region and IR excess beyond 10 micron; we also report the detection of synchrotron radiation from the supernova.

2. Observations and analysis

Polarimetric observations of SN1987A were made on the 1 meter telescope at Kavalur of Indian Institute of Astrophysics, Bangalore, on March 6 and 7 using standard B, V and R filters of Johnson-Morgan system and have already been reported in IAU Circular (Raveendran et al., 1987). The instrument and the method of observation and

Table 1 : Polarimetric observations of SN1987A; degree of polarization (P) and position angle (θ) in different wavebands are expressed respectively in percent and degrees. Errors in last figure stated are given in parantheses.

	U		B		V		R		I		
	P	θ	P	θ	P	θ	P	θ	P	θ	Source
25.4 FEB	1.01 (10)	34 (4)	0.97 (6)	36 (2)	0.83 (8)	46 (4)	0.86 (6)	44 (3)	0.81 (4)	41 (2)	Cropper et al. 1987
28.2 FEB	0.92 (22)	39 (19)	0.92 (18)	26 (16)	0.964 (94)	39.8 (79)	0.855 (14)	39.4 (14)	0.682 (36)	36.3 (43)	Barrett 1987a.
2.3 MAR	0.58 (11)	29 (15)	0.92 (10)	38 (9)	*0.848 (88)	*34.8 (85)	0.786 (76)	38.2 (79)	0.642 (104)	41.2 (131)	Barrett 1987a.
6.65 MAR			0.64 (4)	26 (4)	0.75 (6)	37 (5)	0.74 (4)	27 (3)	0.70 (8)	31 (6)	Present Obs.
7.3 MAR	0.58 (6)	48 (3)	0.64 (6)	35 (3)	0.63 (7)	33 (3)	0.60 (5)	36 (2)	0.58 (7)	31 (3)	Schwarz 1987.
7.63 MAR			0.74 (4)	30 (3)	0.70 (1)	49 (1)	0.68 (3)	29 (3)	0.69 (7)	22 (6)	Present Obs.
15 MAR	2.30 (36)		0.56 (6)		0.61 (6)		0.60 (4)		0.55 (4)		Benvenuto et al. 1987
21 MAR	0.51 (10)	58 (5)	0.51 (7)	37 (4)	0.49 (7)	47 (5)	0.53 (5)	40 (3)	0.44 (4)	41 (3)	Ogura and Sato, 1987
22 MAR			0.50 (7)		0.52 (5)		0.54 (5)		0.38 (5)		Benvenuto et al. 1987

Notes : i) Asterisked data is for March 1

ii) Data on March 15 and 22 - the authors have reported θ to be almost constant at 40±3 degrees.

reduction is discussed elsewhere (Deshpande et al., 1985, Joshi et al., 1987). Table 1 lists the polarization data on different dates available from the literature along with our observations. Figure 1 shows the wavelength dependence of polarization on different dates and figure 2 shows time variation of polarization in different bands.

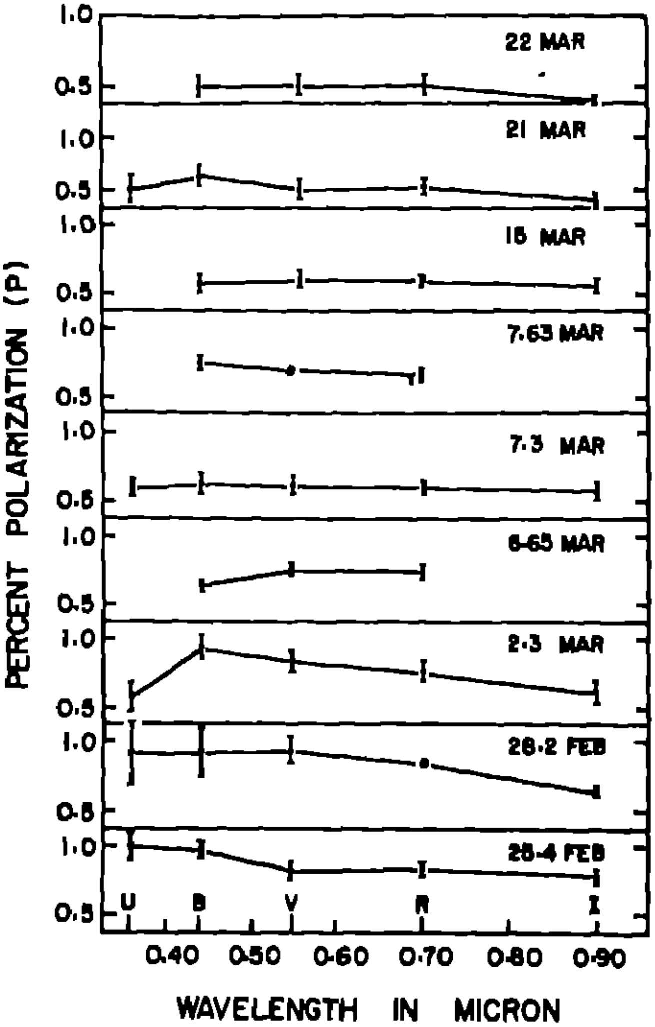

Figure 1 Wavelength dependence of polarization of SN 1987A on various dates. Error bar (±) are also marked.

3. Interstellar Polarization:

Schwarz and Mundt (1987) have adopted the interstellar polarization value P_{is} = 0.97% and θ = 39 degrees, which has been given by Barrett (1987a) for a comparison star. In the subsequent observations of March 7 and 8, Barrett (1987b) has reported a decrease in the polarization of the comparison star. The degree of expected interstellar polarization (P_{is}) is estimated as follows:

The reddening value for SN1987A has been given by several authors. We take E(B-V) = 0.20 (Blanco et al., 1987) which corresponds to an extinction of $A_V \sim 0.64$ in the visual band, assuming R=3.20. The ratio of polarization to the extinction in visual due to the interstellar dust is typically $(m_p / A_V)_V \sim 0.025$ (Greenberg, 1978) where m_p is the degree of interstellar linear polarization expressed in magnitude scale and A_V is attenuation due to interstellar medium. This relationship gives $p_{is} \sim 0.8\%$. Therefore the expected p_{is} is nearly same as the observed value of polarization for SN1987A. However, the observed value of polarization shows a systematic decrease in polarization with time in all bands. The polarization in U-band shows some fluctuations. This shows

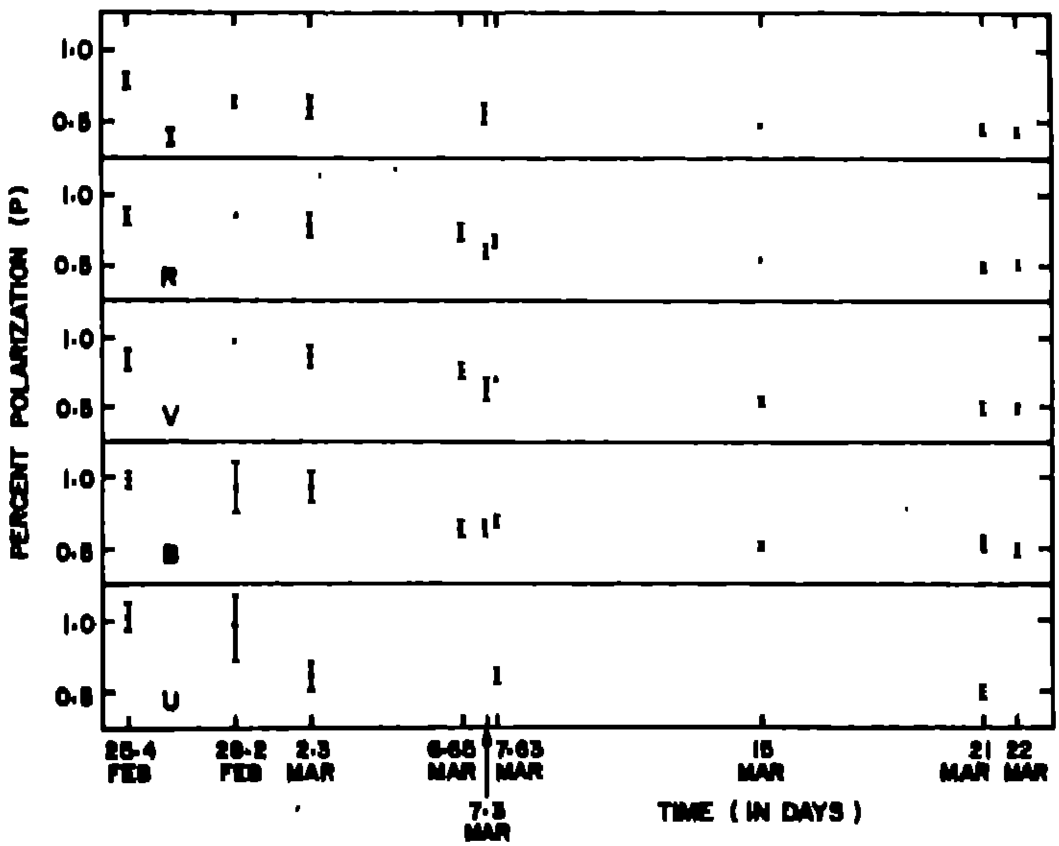

Figure 2 Variation of degree of polarization in various Wavebands with time.

that the observed polarization has intrinsic component. We have plotted the polarization data in $Q=P\cos 2\theta$; $U=P\sin 2\theta$ plane in figure 3 to study the time dependent behaviour of the observed polarization. These parameters are the components of the polarization vector in the (Q,U) plane and are additive for intrinsic and interstellar polarization. The observed polarization points are expected to define a straight line in (Q,U) plane under the following assumptions:

a) the observed polarization is a mixture of intrinsic and interstellar polarization;

b) the observed polarization decreases with time. We assume that only intrinsic component decreases while P_{is} remains constant. We also assume $\theta_{intrinsic}$ remains constant with time.

The slope of the line would be twice the intrinsic polarization angle 2θ. The distribution of points in Q-U plane in figure 3 is quite random and it is not possible to fit a straight line to the observed points. This indicates that $\theta_{intrinsic}$ also changes with time. This is possible when there are two sources producing polarization, both or one of which is varying with time.

4. Discussion

Figure 2 shows the time dependence of polarization. The degree of polarization shows a gradual decrease between February 25 and March 22 1987. The small fluctuations in position angles in different wavelength bands (Table 1) on different dates could be due to variations in intrinsic polarization. In order to study the polarization behaviour of SN1987A in more detail we have plotted in Figure 1 the wavelength dependence of polarization on different dates. Before March 6 the wavelength dependence of polarization resembles the polarization produced by a dust layer in front of the source. However, on March 7, 15 and 22 there is no significant variation in the polarization with wavelength. The error in the polarization measurements in U-band on February 22 and March 15 by Benvenuto et al. (1987) are quite large and are not plotted in figure 1. Also the U-band data shows comparatively large fluctuations. The observed polarization behaviour has been explained in terms of the dust shell model discussed later.

The wavelength dependence of polarization on February 28 and on March 2 and 6 (Figure 1) shows that the P_{max} lie between B and V bands which is indicative of the size of the dust particles to be smaller than the interstellar grain size.

Circular polarization (q) in V-band as measured by us on March 7 is q~2.3*10exp(-4). Circular polarization has also been measured by Barrett (1987a,b) on February 28 and March 2, 7 and 8 in UBVRI bands. Our measurement of q in V-band on March 7 is in close agreement with the value reported by Barrett (1987b). An interstellar origin for the detected circular polarization is to be excluded for the following reasons. The maximum inter-stellar q for twisting alignment of the grains along the line of sight is

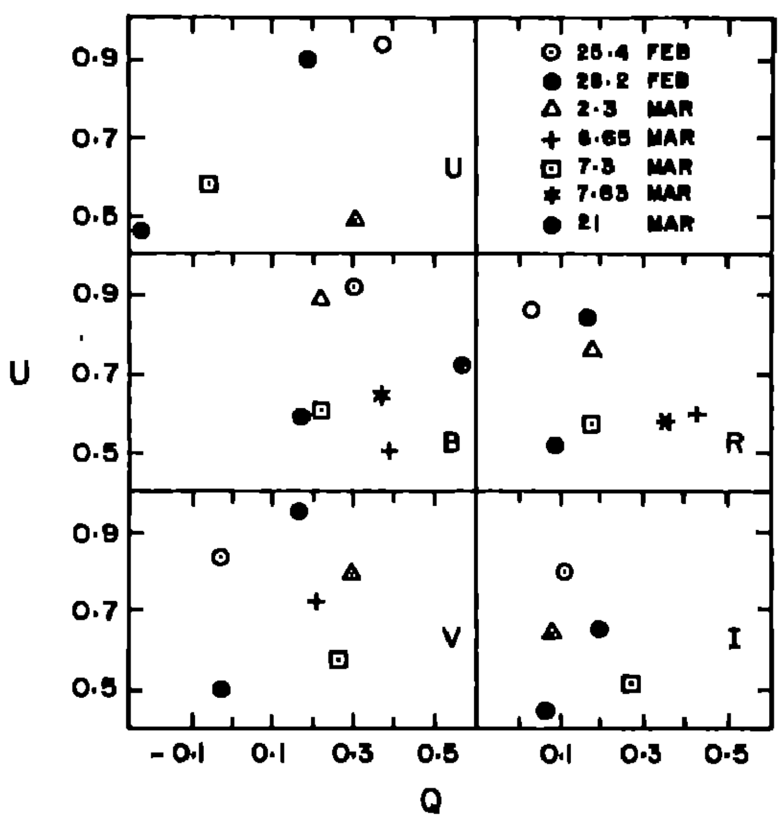

Figure 3 Distribution of observed polarization in (Q, U) plane; points on different dates are marked with different symbols.

expected to be $q \sim 1/3\ (p_{is})^2$ (Kemp and Wolstencroft, 1972; Martin, 1974). The expected interstellar polarization as estimated above is $p_{is} \sim 0.8\%$ for supernova. This gives $q \sim 2*10exp(-5)$ which is lower than the detected polarization by one order of magnitude. It appears that the observed q is due to the intrinsic linear polarization converted to circular polarization due to the combined effect of circumstellar dust and foreground interstellar dust; the expected q would be $q_{max} \sim p_{dust}*P$, where p_{dust} is polarization due to dust in the shell and interstellar medium. Adopting $P \sim 1.0\%$ and $p_{dust} \sim 1.0\%$ we get $q_{max} \sim 1.0*10exp(-4)$ which is close to the observed q. Multiple scattering is also expected to produce circular polarization. Observations on circular polarization on February 28 shows change of sign near V-band. Circular polarization data on other dates- March 2,7 and 8 also shows change in sign, but at differing wavelengths. The change of sign in wavelength dependence of q is a characteristic of polarization produced by dust scattering (Greenberg, 1978). The circular polarization is perhaps produced by circumstellar dust and interstellar medium by converting the already polarized light to circularly polarized light. The degree of circular polarization is relatively large on February 28 and drops to lower values on later dates. These observations thus indicate the presence of the dust shell around SN1987A. Figure 2 shows the change in polarization with time. The magnitude of change with time in polarization is much slower than the change in flux especially in U and B bands (Hamuy, 1987). This further supports the presence of dust shell around SN1987A.

5. Dust shell model

Bode and Evans (1980) suggested that the thermal emission from SN1979c and SN1980k originate from the pre-existing dust in a circumstellar shell heated by the UV-visual output of the supernova. This possibility was also suggested by Chevalier (1982). Dwek (1983) based on the dust shell model explained for SN1979c and SN1980k the thermal infrared emission in terms of IR echo of a supernova with the circumstellar dust shell. The polarimetric observations seem to be consistent with the circumstellar dust shell model in the present case. As it has been discussed earlier, linear polarization is a mixture of atleast two components - one produced due to the presence of dust shell. The wavelength dependence of polarization on different dates (Figure 1) shows that the dust scattering contribution to polarization dominates in early phases upto March 7. However, on March 7.3 and beyond, the wavelength dependence of polarization is almost flat and perhaps the net polarization due to dust has decreased and the other component dominates. This can be explained in terms of a similar model which Dwek (1983) has used to explain the IR emission in SN1979c and SN1980k.

We assume a spherically symmetric dust shell around the progenitor star. The dust shell is due to the mass loss from the pro-genitor star during its evolution. A star of 20M☉ is expected to lose a significant fraction of its mass during its evolution.

The proposed model is as shown in Figure 4. Due to the finite light travel time, the scattered light for larger θ shall arrive at a later time to the observer than for the smaller θ. As long as θ is small and the grains are aligned in the shell, the observed polarization would be similar to interstellar polarization. With time θ increases and the net polarization would be averaged to negligible value. Therefore in the early phases polarization due to dust in the shell would dominate and this is what we observe.

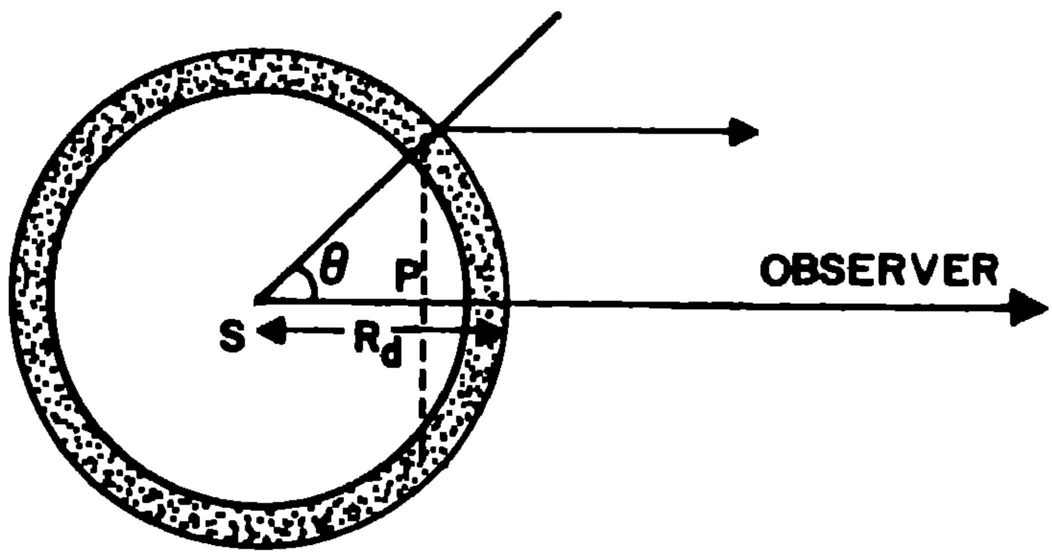

Figure 4 Schematic of the proposed dust shell model around supernova SN 1987A.

The radius of the dust shell has been deduced as follows:

We assume that the polarization due to dust shell will be averaged to small value when θ exceeds 45 degrees. From the observations (Figure 1) we find that the wavelength dependence of the polarization is flat after March 7th i.e. after 13th day from the explosion. Assuming that the contribution to the observed polarization due to the dust is negligible after t=13 day of the explosion, the radius of the dust shell is estimated by: $R_d = ct/(1-\cos\theta)$ where c is velocity of light and t is the light travel time for the distance (R_d-SP) (vide: Figure 4). Taking t=13 day and θ=45 degrees, we get $R_d \sim 0.04$pc.

We assume that during the first few days the intrinsic polarization is mainly due to the dust shell. Taking interstellar polarization value reported by Barrett (1987a), the intrinsic polarization on February 25.4 comes out to be $p_{sn} \sim 0.8\%$. On very early phases after the explosion the synchrotron component is expected to be weak. When the expanding envelope starts becoming optically thin the onset of synchrotron radiation is expected. Taking $p_{sn} \sim 0.8\%$ in visual band as produced by dust in the shell, $m_p / A_v \sim 0.025$ (Greenberg, 1978) and $A_v = 1.086 * \tau_d$, the optical depth of the shell is estimated to be 0.6. The above model has been checked and found to explain the IR excess found at waveband N3(12.89 micron) by Bouchet et al.(1987). The IR flux due to the dust shell has been calculated assuming isothermal and thin shell model. Under these assumption the flux at wavelength λ and time t can be expressed as:

$$F(t) = (a^2/D^2) * V(t) * nd(R) . \pi B_\lambda (T_d) * \overline{Q}_\lambda$$

where a, D, R, V(t), nd, $\overline{Q}_\lambda$, and $B_\lambda(T_d)$ are respectively grain size, distance of SN1987A from the observer, radius of the dust shell, volume of the emitting region at time t, number density of the grains, emission efficiency and Planck function.

Writing $V(t) = 2\pi . R_d . c . t . \Delta R$; and $\tau_d = a^2 Q_\lambda * nd * \Delta R$; where Q_λ is absorption efficiency of the grains in UV and ΔR is the geometrical thickness of the shell, the expression for the flux is re-written as:

$$F_\lambda(t) = (2\pi/D^2)*R_d.C.t.\tau d.B_\lambda(T_d)*\bar{Q}_\lambda$$

Here Q has been taken as 1.0.

Using this expression and taking D=55kpc for SN1987A and a=0.1 micron and adopting the emission efficiencies from Draine and Lee (1985) the IR excess at 12.89 micron can be explained if the dust temperature is 200±50 K. The observed flux and blackbody flux at 12.89 micron as estimated by Bouchet et al. (1987) on March 11 are respectively 1.07*10exp(-6) and 6.11*10exp(-7) ergs s^{-1} cm^{-2} μ^{-1} The dust shell contribution to the flux at 12.89 micron as calculated for the model given above is 4.3*10exp(-7) ergs s^{-1} cm^{-2} μ^{-1} which satisfactorily explain the IR excess at 12.89 micron. The slight IR excess at 10.2 micron can also be attributed to the dust shell.

6. Conclusions

Time variation of wavelength dependence of linear polarization is suggestive of a dust shell around SN1987A. The intrinsic polarization is due to atleast two components: one is due to dust shell and other is perhaps synchrotron component. The minimum radius of the dust shell is estimated to be 0.04 pc with optical thickness at visual wavelength 0.6. The temperature of the dust shell is expected to be $T_d \sim 200K$.

Acknowledgement

The authors are grateful to Prof. J.C.Bhattacharyya for making telescope time available on the 1m telescope of Indian Institute of Astrophysics, Kavalur. We are thankful to Prof.R.K.Varma and Prof. P.V.Kulkarni for encouragement. We are also thankful to Dr N.K.Rao for helpful discussions. The research programme is supported by the Department of Space, Government of India.

References

Bailey, J.A. 1987, IAUC 4351
Barrett, P. 1987a, IAUC 4337
Barrett, P. 1987b, IAUC 4340
Benvenuto, O., Cloochiatti, A., Feinstein, C., Garcia, B., Luna H., Mendez, M., Morrell, N. 1987, IAUC 4358.

Bode, M.E., Evans, A. 1980, Monthly Notices Roy.Astron Soc.193,21p.
Blanco, V.M., Gregory, B., Hamuy, M., Heathcote, S.R., Phillips, M.M., Suntzeff, N.B., Terndrup, D.M., Walker, A.R., Williams, R.E., Pastorizo, M.G., Storchi-Bergmann, T.Mathews, J. 1987, Astrophys. J. 300, 585.
Bouchet, P., Stanga, R., Le Bertre, T., Epchtein, N., Hammann, W.R., 1987, ESO Preprint No.550,10
Chevalier, R.A., 1982, Astrophys. J. 259, 302.
Croper, M., Bailey, J.A., Peacock, T.I., Wickramasinghe, D.T., 1987, IAUC 4319.
Deshpande, M.R., Joshi, U.C., Kulshrestha, A.K., Banshidhar, Vadher, N.M., Mazumdar, H.S., Pradhan, N.S., Shah, C.R., 1985, Bull.Astron.Soc.India 13 157.
Draine, B.T., Lee, H.M., 1985, Astrophys.J. 290, 211
Dwek, E., 1983, Astrophys. J. 274, 175.
Dwek, E., A'Hearn, M.F., Becklin, E.E., Hamilton Brown, R., Capps, R.W., Dinerstein, H.L., Gatley Ian, Morrison, D., Telesco, C.M., Tokunaga, A.T., Werner, M.W., Wynn-Williams, C.G., 1983, Astrophys. J. 274, 168.
Greenberg, J.M., 1978, in Cosmic Dust, ed Mc Donnell, J.A.M., Wielly.
Hamuy, M., 1987, NOAO Preprint No.102.
Joshi, U.C., Deshpande, M.R., Sen, A.K., Kulshrestha, A., 1987, Astron.Astrophys. 181, 31.
Kemp J.C., Wolstencroft R.D., 1972, Astrophys. J.(Letters) 176 1115.
Malkan, M., Sun, W. -H. 1987, IAUC 4353.
Martin P.C., 1974, Astrophys. J. 187, 461.
Ogura, K., Sato, S., 1987, IAUC 4351.
Raveendran, A.V., Joshi U.C., Vadher, N.M., Rao, N.K., 1987, IAUC 4339.
Schwarz, H.E., 1987, IAUC 4339.
Schwarz, H.E. and Mundt, R., 1987, Astron. Astrophys. 177, L4.