POLARIMETRIC AND PHOTOMETRIC OBSERVATIONS OF SPLIT COMET C/2001 A2 (LINEAR)

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Abstract. We present the results of polarimetric and photometric observations of split Comet C/2001 A2 (LINEAR), which were obtained at the 70-cm telescope of the Astronomical Observatory of Kharkiv National University between 30 June and 31 July 2001. The brightest fragment of the comet, nucleus B, was observed. Eight narrowband cometary filters in the continuum and in emission bands and a wideband red filter have been used. The comet was observed through apertures of 88, 33, and 19 arcsec. Polarization phase curves were obtained for the continuum and for the first time, for NH_2(0, 7, 0) emission. The degree of polarization of the light scattered by the dust decreases with the increase of aperture size. An important temporal variation of the polarization with a rotation of the polarization plane was observed at two phase angles (26.5° and 36.2°). Molecular column densities and production rates of CN, C_2, C_3, and NH_2 species are calculated in the framework of the Haser model. A comparative analysis of the temporal variations of the visual magnitudes, gas and dust production rates, dust color and polarization are presented.

Keywords: Comet C/2001 A2 (LINEAR), comets, dust, NH_2, polarization

1. Introduction

A partial fragmentation or complete disintegration of comets should be accompanied by ejection of the fresh internal material and therefore, provide a good opportunity to study the inner composition of nucleus and physical processes occurring in the atmosphere of splitting comets. Taking into account the unpredictable nature of such events, dust and gas monitoring observations of fragmenting comets are very sparse.

Comet A2 (LINEAR), hereafter called C/A2, displayed a series of sporadic outbursts due to disruption of its nucleus. According to Sekanina (2001), the initial splitting of the nucleus on fragments A and B occurred on March 29.9, 2001. The following separation of components C, D, E, and F from the nucleus B occurred respectively on May 11, June 3.5, June 9.5, and June 11.3. The favorable brightness predictions made this comet a suitable target for polarimetric and photometric observations even with small-sized telescopes.

Therefore, the purpose of our observations was to determine gas and dust production rates of the nucleus and to measure the linear polarization of light

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scattered by dust in order to find their possible variations caused by disruption of the cometary nucleus.

2. Observations

Comet C/A2 was observed after its perihelion passage that occurred on 24 May 2001, when its closest approach to Earth was at 0.24–0.51AU. Polarimetric observations were carried out for 17 nights from 30 June to 31 July 2001 with narrowband and wideband filters. The comet was observed by narrowband photometry during three nights. Measurements were obtained with the 70-cm telescope of the Astronomical Observatory of Kharkiv National University. A single-channel photoelectric photometer–polarimeter with a rapidly rotating polaroid (Kiselev and Velichko, 1998) was used. The HB and ESA set filters were used in order to isolate emission bands CN (λ387/6.2 nm), C_3 (λ406.2/6.2 nm), C_2 (λ514.1/11.8 nm), NH_2 (λ663/4 nm) and the ultraviolet λ344.8/8.4 nm (UC), blue λ445/5 nm (BC), green λ526/5.6 nm (GC), and red λ712.9/6.2 nm (RC) continuum ranges. The wideband filter λ722.8/114 nm (WRC) was also used for polarimetric observations. The 19, 33 and 88 arcsec diaphragms were employed. Several standard stars taken from (Farnham et al., 2000) were observed to convert the cometary counts to absolute fluxes.

3. Results

3.1. Photometry

The photometric reductions and computations of the Haser-model production rates Q for CN, C_3, and C_2 molecules were performed in a standard manner (Kiselev and Velichko, 1998). The absolute fluxes for standard stars in NH_2 filter were taken from (T. Bonev, personal communication). To determine the gas production rate for NH_2 we used a fluorescence efficiency value $g = 2.29 \times 10^{-15}$ (erg s^{-1} mol^{-1}) for the (0, 7, 0) band as calculated by (Kawakita et al., 2001). The lifetimes for NH_2 and its parent (1.0×10^5 s and 5.0×10^3 s, respectively) have been provided by (Korsun and Jockers, 2002).

The photometric results are listed in Table I with the log of the observations (time of observations, heliocentric r and geocentric Δ distance, phase angle α, projected diaphragm radius at the comet ρ).

The dust-equivalent $A(\alpha)f\rho$ production rates and color of dust were calculated according to (Farnham et al., 2000) and are presented in Table II. The last column in this table gives the equivalent width W_{4845} of the $C_2(0, 0)$ emission band characterizing the ratio of gas-to-dust in the cometary atmosphere. One can see that the gas-to-dust ratio in the large diaphragm was about 1000 Å for all dates of

TABLE I
Gas production rates for Comet C/2001 A2 (LINEAR)

Date, UT	r	Δ	α	ρ	log Q (mol s^{-1})			
July 2001	(AU)	(AU)	(deg)	(10^4 km)	CN	C_3	C_2	NH_2
14.960	1.231	0.320	42.0	1.020	25.60	25.06	25.94	24.65
14.994	1.232	0.320	41.9	0.388	25.63	25.08	25.94	24.73
17.888	1.271	0.349	37.6	1.114	25.53	24.83	25.74	24.46
31.990	1.463	0.529	26.1	1.688	25.52	24.89	25.74	24.51

TABLE II
Dust data for Comet C/2001 A2 (LINEAR)

Date, UT	log A(α)fρ (cm)				CE (%/1000 Å)			W_{4845}(Å)
July 2001	UC	BC	GC	RC	UC–BC	BC–GC	GC–RC	
14.960	2.67	2.59	2.55	2.73	–18.5	–9.6	21.5	1083
14.994	2.55	2.58	2.52	2.70	8.4	–16.8	21.1	562
17.888	2.54	2.51	2.46	2.65	–7.4	–14.4	23.1	898
31.990	–	2.52	2.46	2.65	–	–16.2	22.8	958

observations. Such value of the equivalent width is typical for gas-rich comets (Chernova et al., 1993). At the same time, there is the significant reduction of W_{4845} for small diaphragm. Thus, this comet seem to be gas-rich for large apertures and dust-rich for small apertures. It means that the concentration of the dust is higher in the circumnuclear region.

Dust in the comet was bluer relatively to the Sun in the wavelength range λ345–526 nm and redder in the wavelength range λ526–712.8 nm. There are two possible ways for an explanation of this observation: (1) Inherent properties of dust in this comet, and (2) the incomplete correction of contamination from gas emission, especially for the UC and BC filters.

As one can see from Table I, there is the decrease of the molecular and dust production rate from 14 to 17 July. The gas-to-dust ratio also decreased during this period. Note that this decrease falls on a descending branch of outburst, which occurred near 13 July. It is clearly seen in Figure 1, where the brightness evolution of Comet C/A2 during our observating campaign is shown.

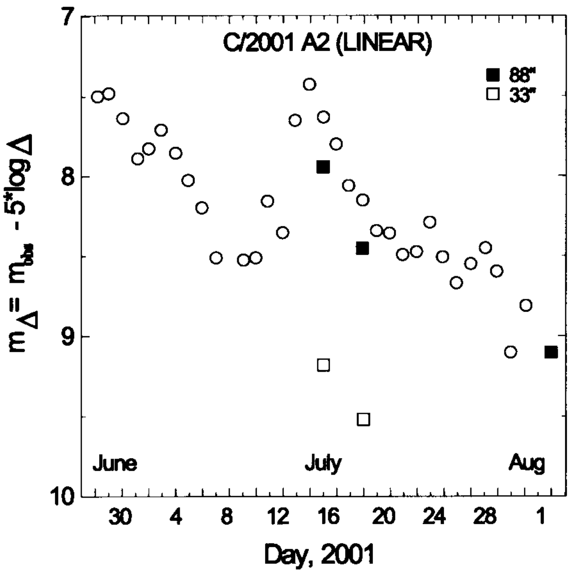

Figure 1. Brightness evolution of Comet C/A2 during our observations. The circles show averaged visual magnitudes (m_{obs}) taken from (ICQ, 2001) and reduced to the geocentric distance Δ=1 AU (m_Δ). The squares denote our relative photoelectric magnitudes in GC filter.

3.2. POLARIMETRY

The results of the polarimetric observations are given in Table III, which contains the degree of linear polarization P, the position angle Θ of the polarization vector, their statistical mean-square errors, the position angle of the scattering plane φ and the difference between the plane of polarization and the normal to the scattering plane Θ_r for different moments, phase angles, filters, and diaphragms.

The phase angle dependence of polarization for C/A2 is presented in Figure 2. One can see, that at large phase angles (between 31 June and 7 July), the polarization degree of the comet was lower than that usually observed for dusty comets. Besides, the degree of polarization measured with large aperture, which corresponds to the projected diaphragm radius $\approx$ 8000 km at the coma, is distinctly less than that with smaller apertures. In the near-nuclear region (ρ = 3250 km, on July 8.95 UT), the polarization of C/A2 was similar to that of dusty comets. Such effect was also observed for two other gas-rich comets: Comet D/1996 Q1 (Tabur) (Jockers, 1997), which was also a split comet, and Comet 2P/Encke (unpublished data by N. N. Kiselev et al.). A strong diaphragm dependence of polarization for gas-rich comets may be caused by incomplete correction of contaminations from gas emission bands or by change of intrinsic dust properties with distance from nucleus. The polarization degrees of dust and gas are practically equal at phase angles less than 40°. Therefore, in the first case, the difference between gas-rich

TABLE III
Polarization of Comet C/2001 A2 (LINEAR)

Date, UT 2001	Filter	ρ (km)	α (deg)	P (%)	σ_P (%)	Θ (deg)	σ_Θ (deg)	φ (d eg)	Θ_r (deg)
June									
30.978	WRC	7780	74.8	13.68	0.23	156.1	0.5	246.9	–0.8
July									
01.976	WRC	2928	72.1	16.26	0.24	158.4	0.4	247.1	1.3
02.967	WRC	1696	69.3	17.38	0.35	157.1	0.6	247.0	0.1
03.951	RC	7930	66.6	16.04	0.85	150.4	1.5	246.6	–6.2
03.987	NH_2	7935	66.5	9.09	0.40	155.0	1.2	246.6	–1.6
04.933	NH_2	8032	64.0	7.40	0.59	149.8	2.3	246.0	–6.2
04.975	RC	8036	63.9	9.12	0.70	162.2	2.2	245.9	6.2
06.946	RC	8307	58.7	14.02	0.50	153.5	1.0	244.0	–0.5
08.950	RC	3252	53.9	14.07	1.11	149.7	2.3	241.1	1.4
15.894	RC	3935	40.5	5.42	0.66	137.8	3.5	226.3	1.5
16.873	NH_2	10808	39.0	4.23	0.37	125.7	2.5	223.8	–8.1
16.961	RC	10838	38.9	4.68	0.39	131.6	2.4	223.6	–2.1
18.859	BC	11488	36.3	3.91	0.39	125.8	2.8	218.6	–2.8
18.954	RC	11521	36.2	5.61	0.44	123.6	2.2	218.3	–4.7
19.908	RC	2563	35.0	–4.86	1.22	49.3	7.2	215.7	103.6
20.873	RC	4584	34.0	4.06	1.02	156.9	7.2	213.1	33.8
20.975	RC	12638	32.8	2.14	0.55	116.4	7.4	210.0	–3.6
21.990	NH_2	12638	32.8	4.69	0.66	113.1	4.0	209.9	–6.8
26.925	RC	14616	28.8	2.67	0.64	79.2	6.9	196.0	–26.8
26.972	WRC	14648	28.7	2.51	0.25	114.6	2.8	195.9	8.7
28.887	WRC	15478	27.6	1.82	0.26	86.6	4.1	190.5	–13.9
28.892	WRC	5804	27.6	1.80	0.24	106.1	3.9	190.5	5.6
28.951	WRC	3348	27.6	2.18	0.25	120.4	3.3	190.3	2.1
29.939	NH_2	15956	27.0	4.11	1.15	95.4	8.0	187.6	–2.2
30.952	RC	16403	26.5	–2.36	1.03	0.5	12.5	184.8	85.7

and dust-rich comets as well as the diaphragm dependence of polarization should disappear with decreasing phase angle.

We have found that the spectral gradient dP/dλ of dust polarization for Comet C/A2 was 0.63 ± 0.22%/100 nm at $\alpha = 36.3°$. For comparison, the mean value of the spectral gradient for dusty comets is equal to 0.84 ± 0.03%/100 nm at phase angle 45° (Kiselev, 2002). Taking into account that the gradient dP(λ)/d$\alpha = 0.025 \pm 0.001$%/100 nm per 1° is constant within the phase angle range 30–65° (Kiselev,

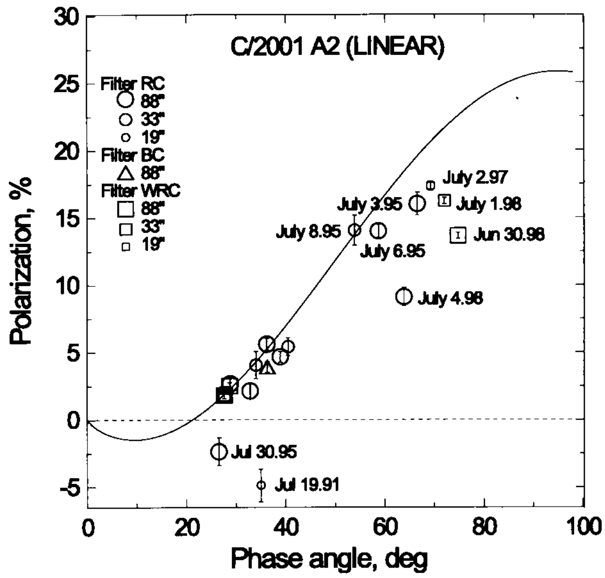

Figure 2. Polarization degree of Comet C/2001 A2 (LINEAR) as compared with the trigonometric fit for dusty comets in the red continuum filter (solid curve).

2002), we conclude that the wavelength dependence of polarization for C/A2 is close to that commonly observed for dusty comets.

Several interesting features were detected in polarization data of C/A2. On July 4.98 at phase angle 63.9°, a very small polarization of about 9% has been observed. Moreover, usually the plane of polarization is perpendicular to the scattering plane at phase angles larger than 22°, e.g., positive polarization is observed. It is surprising, that a change of the polarization plane relative to the scattering plane was detected at phase angles 35° and 26° on July 19.91 and 30.95. We could not explain these results by instrumental errors. The normal operation of the polarimeter was controlled by observations of standard stars with zero and large polarization during all observing nights. However, it is important to note, that these polarimetric features coincide in time with the outburst activity of the comet.

The most important molecule in the red spectral region is NH_2, which falls within the passbands of the used continuum filters. Theoretical as well as observational data on polarization of light emitted by these molecules are practically absent. Five measurements of polarization were obtained through the filter, which transmits radiation of molecules NH_2(0, 7, 0) and continuum. The continuum flux F_{cont} in the NH_2(663/4 nm) filter was determined from the continuum fluxes in the GC and RC filters. It allowed us to define the relative contribution of the NH_2(0,7,0) emission F'_{NH_2} and continuum F'_{cont} in the NH_2(663/4 nm) filter. Using equation $P_{(NH_2+cont)} = P_{NH_2} F'_{NH_2} + P_{cont} F'_{cont}$, a "clear" polarization P_{NH_2} of the NH_2(0, 7, 0) radiation was calculated. In this equation $P_{(NH_2+cont)}$ is the observed polarization degree in the NH_2(663/4 nm) filter and P_{cont} is polarization degree of dust in the

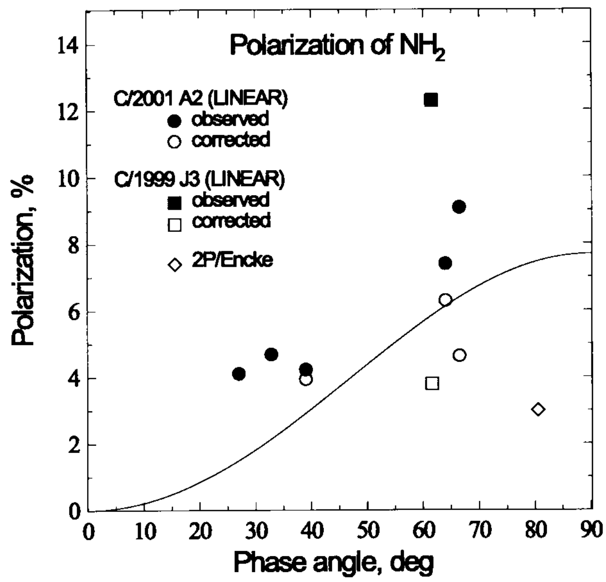

Figure 3. Polarization measurements of the cometary radiation of $NH_2(0, 7, 0)$ molecules in Comet C/2001 A2 (LINEAR). For comparison, the available data for comets C/1999 J3 (LINEAR) (Jockers, unpublished) and 2P/Encke (Kiselev et al., unpublished) are given. The solid curve is the phase angle dependence of polarization for the resonance fluorescence scattering (Le Borgne and Crovisier, 1987).

NH_2(663/4 nm) filter obtained by interpolation of the polarization degree in the GC and RC filters. The continuum contribution in the observed polarization of NH_2 reached 5% for C/A2. The observed and corrected degree of polarization for comets C/A2, C/1999 J3 (LINEAR) and 2P/Encke can be found in Figure 3. This figure shows that polarization of NH_2 is about the same as the polarization of the diatomic molecules C_2 and CN (Le Borgne and Crovisier, 1987).

4. Discussion

The study of Comet A2 (LINEAR) is important from two points. First, it is a split comet. And second, this comet is a gas-rich one. We have observed C/A2 (namely, nucleus B) in the active phase when its brightness varied rather considerably, with amplitude up to 1.5^m (Figure 1). Although we do not have an extensive set of photometric data for this comet, we can mark some its peculiarities.

To compare gas and dust production rates in split comet C/A2 with those in typical comets, we have determined the following ratios of production rates: $Q(C_3)/Q(CN)$, $Q(C_2)/Q(CN)$, $Q(NH_2)/Q(CN)$, and $A(\alpha)f\rho/Q(CN)$ (Table IV). The production rate ratios $Q(C_3)/Q(CN)$ and $Q(C_2)/Q(CN)$ in comet C/A2 are close to the upper limits for other comets (A'Hearn et al., 1995). The production rate

TABLE IV
Production rate rations of Comet C/2001 A2 (LINEAR)

Ratio	C/A2	Limits	Comets
Log [Q(C_3)/Q(CN)]	–0.61	–1.74 ÷ –0.51	Typical comets[a]
Log [Q(C_2)/Q(CN)]	0.27	–0.20 ÷ 0.24	Typical comets[a]
Log [Q(NH_2)/Q(CN)]	–0.98	0.26	C/1998 J3 (LINEAR)[b]
Log[A(α)fρ/Q(CN)]	–23.02	–24.63 ÷ –21.87	Typical comets[a]

[a] A'Hearn et al. (1995).
[b] Korsun and Jockers (2002).

ratio Q(NH_2)/Q(CN) was compared with that for the gas-rich Comet C/1999 J3 (LINEAR). This comet was a unique comet, which was observed in the same (0,7,0) band (Korsun and Jockers, 2002). It turned out that the relative content of NH_2 in comet C/A2 was about 18 times lower than that for J3 (LINEAR). Finally, we have estimated the averaged ratio A(α)fρ/Q(CN), which is within the limits for typical comets.

Variations among the continuum colors of comets do not appear to be correlated with heliocentric distance, phase angle, or dust production (Jewitt and Meech, 1986). Color differences apparently arise from intrinsic variations of dust grain properties in comets. Figure 4 shows that in the color diagram UC–BC versus BC–RC, comet C/A2 lies between very dusty comets C/1995 O1 (Hale–Bopp), C/1990 K1 (Levy), C/1996 B2 (Hyakutake) and very gas-rich comets 23P/Brorsen–Metcalf and C/1989 X1 (Austin). The light scattered by the dust in dusty comets is generally redder than the Sun. According to (A'Hearn et al., 1995), the light scattered by gas-rich comets seems to generally be bluer. These authors have noted that this effect may be artificial due to the gas contamination in the continuum filters. In particular, the ultraviolet continuum is contaminated by the short-wavelength wing of the C_3 emission. The C_2 emission can extend into the BC filter. New procedures developed by (Farnham et al., 2000) allow to remove contamination by different emissions. It is impotrant to note that comet C/A2 was more dusty in the small diaphragm (Table II). Simultaneously its color has changed: the UC–BC color became redder and the BC–GC color – bluer relatively to colors in the large diaphragm. It is possible that the correction for the gas emission contamination was incomplete. Moreover, the intrinsic properties of dust may be different throughout the coma. Therefore, the question of the blue color of gas-rich comets remains still open.

Since C/A2 was a gas-rich comet, it is interesting to compare its polarization with that for other gas-rich comets (e.g., C/1983 H1 (IRAS–Araki–Alcock), C/1989 X1 (Austin), 23P/Brorsen–Metcalf), and D/1996 Q1 (Tabur) (see Figure 5). For Comet Tabur, the observed polarization and the one corrected for the NH_2 contamination are given. The used data set for other comets are not free of emission by gas. The projected aperture for Comet IRAS–Araki–Alkock was 700–1900

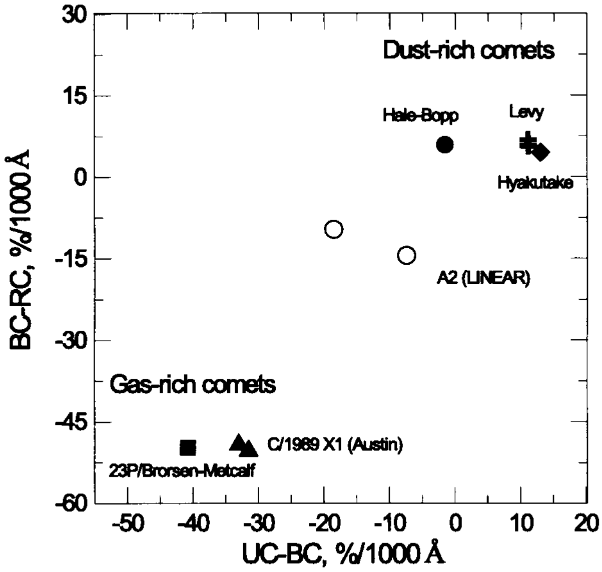

Figure 4. Color diagram UC–BC vs BC–RC for dusty and gas-rich comets. Colors of comets are taken from (Sen et al., 1991; Joshi et al., 1992) for Austin; (Kiselev and Velichko, 1998) for Hyakutake; (Kiselev and Velichko, 1997) for Hale–Bopp; (Kolokolova et al., 1997) for Levy; (Kiselev, 2002) for Brorsen–Metcalf.

km while for comet Brorsen–Metcalf – 6800–37,700 km, and for comet Austin – 75,700–4200 km. There is a clear difference between polarization of the near nucleus area and polarization obtained for large areas of the coma. Furthermore, the polarization degree measured in the wideband filtres is significantly less than that in the narrowband filters because of emission band contamination. In general, the phase angle dependence of polarization for C/A2 is very close to that for comets Tabur and Austin.

Gas-rich comets show an appreciable difference of the positive polarization branch from that for dusty comets. This difference is especially significant for large areas of the coma, few tens of thousand kilometers wide. In the near nucleus region (up to $\approx$1000–2000 km), the polarization degree of gas-rich comets is close to that for dusty comets. It is well seen from Figure 5 for comets Tabur, IRAS–Araki–Alcock as well as for C/A2. There are some possible explanations of these observational facts: (i) Gas contamination in the continuum filters; (ii) the differences in the dust properties in dusty and gas-rich comets; and (iii) different evolution of dust particles in dusty and gas-rich comets.

Outbursts and sudden increases of the dust outflow from the nucleus can cause a change of polarization parameters. Such variations of the polarization degree and plane were measured during the outburst activity in comets 29P/Schwassmann–Wachmann 1 (Kiselev and Chernova, 1979) and C/1990 K1 (Levy) (Rosenbush et al., 1994). Dollfus (1988) has also observed the variations of polarization degree

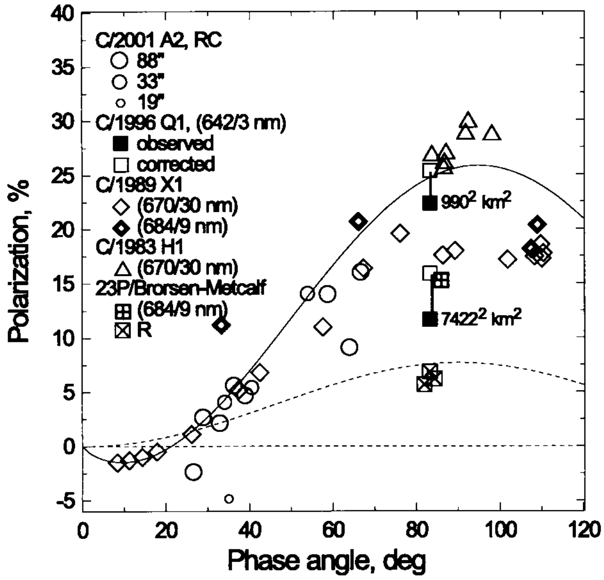

Figure 5. Polarization of Comet C/2001 A2 (LINEAR) as compared with polarization of gas-rich comets Austin (Sen et al., 1991; Joshi et al., 1992; Kikuchi, personal communication), Tabur (Jockers, 1997; Kiselev et al., 2001), IRAS–Araki–Alcock (Kikuchi, personal communication), and Brorsen–Metcalf (Chernova et al., 1993) in the red spectral range. Solid curve is the trigonometric fit to polarization data for dust-rich comets in the RC filter. The dash curve is the phase angle dependence of polarization for the resonance fluorescence scattering (Le Borgne and Crovisier, 1987).

for Comet Halley between the phase angles 50° and 65°. He has interpreted the temporary deviations of polarization in terms of an increased contribution of small dust particles in the cometary atmosphere. We have observed so far unexplained changes of polarization plane and of decrease of polarization degree in C/A2.

5. Conclusions

From our photometric and polarimetric observations of split comet C/2001 A2 (LINEAR), the production rates of CN, C_3, C_2, and NH_2, the quantity $A(\alpha)f\rho$, the dust color, gas-to-dust ratio, and polarization of dust and the NH_2 molecule emission band are determined. The results obtained allow us to make the following conclusions:

– The comet had high gas-to-dust ratio and therefore can be classified as a gas-rich comet;
– according to the relative abundances of C_3/CN and C_2/CN, comet C/A2 lies on upper limit of the range defined for a typical comets;
– the partial fragmentation of the comet has not resulted in global change of its phase dependence of polarization;

- there is short-term variability of the photometric data as well as polarimetric data on a time scale of day. Variations of the polarization degree and plane were detected;
- polarization of the $NH_2(0, 7, 0)$ emission was found, which is close to the theoretical phase-angle dependence of polarization for diatomic molecules.

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