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Studies of Ionized Carbon Regions in Dark Clouds

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Summary. Carbon recombination line emission was detected in only 6 out of 27 regions surveyed in dark clouds with the Parkes 64-m radiotelescope. Compact sources of relatively strong Cnα line emission, such as those in rho Ophiuchus and NGC 2023, therefore appear to be rare. In most cases the non-detections were probably due either to a large dilution factor for the ionizing radiation, or to a low electron density in the cloud. The physical properties of those regions in which lines were detected are discussed; it is suggested that the ratio of sulfur to carbon line intensities may generally be higher in extended, low-electron-density regions, possibly because of a greater propensity for carbon atoms to accrete onto volatile dust grains.

Key words: radio recombination lines — C II regions — dark clouds

Introduction

Carbon recombination lines have so far been detected in 5 dark clouds – rho Ophiuchi, NGC 2023, M78, S140 and NGC 7023 (Brown and Knapp, 1974; Knapp et al., 1975; Brown et al., 1975; Knapp et al., 1976; Pankonin and Walmsley, 1978b). This is an essentially new phenomenon, probably due to carbon Strömgren spheres surrounding early B-type stars embedded in the dark clouds, and provides a different perspective on star formation and the chemistry of the interstellar medium.

The peak of the Cnα line emission occurs near the position of the CO emission peak; the electron temperature is low, comparable with the CO excitation temperature. Other molecular lines seem to be weaker at the position of the C II region, possibly because of dissociation. Near and far infrared sources are also found near the Cnα peak positions, and weak radio continuum sources, probably H II regions, have also been detected in many of the sources at the positions of the B stars.

The carbon recombination line velocities agree well with molecular line velocities. The line widths are also similar, suggesting that microturbulence rather than systematic mass motions dominate the line profiles. This turbulence ($\Delta V_L \sim 1$ km s^{-1}) is less than that for C II regions near H II regions ($\Delta V_L \sim 5$ km s^{-1}), presumably because the exciting star is of a relatively late type. The exceptional narrowness of these recombination lines permits resolution of spectral features due to different heavy elements.

In addition to carbon, a sulfur recombination line has been observed (e.g. Chaisson, 1975); its relative intensity suggests that carbon and other heavy atoms may be depleted due to accretion onto dust grains, although in the presence of dust, line intensities are not simply related to abundances (Cesarsky et al., 1976; Pankonin and Walmsley, 1976).

We have undertaken further observations of carbon recombination lines from dark clouds, in order both to increase the number of known sources and to expand our knowledge of the physical conditions in the line-emitting regions. The 5 known C II regions are from a sample of more than 13 dark clouds searched for recombination line emission; they are distinguished from the others in having associated near- and far-infrared sources, and displaying copious evidence of early-type star activity (Hα and reflection nebulosities, early B-type stars and other young stars, T Tauri stars, Herbig-Haro objects, etc.). We used these criteria to select promising candidates for carbon recombination line emission.

Observations

The observations were made at 1.4 and 5 GHz using the 64-m radiotelescope at Parkes, in November and December 1976. At both frequencies two 512-channel autocorrelation spectrometers were used in parallel in the total power observing mode, with the line frequency present in both signal and reference bands.

The 5 GHz receiver was a dual-channel cooled paramp, giving a system temperature on cold sky of 55 K; the half-power beamwidth was 4$'$.4, and the beam efficiency 0.65. The C109α (5011 MHz) and C110α (4877 MHz) lines were observed simultaneously, and the velocity resolution after Hanning smoothing was 0.47 km s^{-1}. For one source (rho Ophiuchi), the C137β (5008 MHz) and C138β (4900 MHz) lines were also observed. At 1.4 GHz the dual-channel paramp gave a system temperature of 110 K on cold sky, with a beamwidth of 14$'$ and beam efficiency 0.80. Simultaneous observations were made of C166α (1425 MHz) and C167α (1400 MHz), and the velocity resolution after Hanning smoothing was 0.41 km s^{-1}.

The search for carbon recombination line emission was carried out mostly at 5 GHz. This was partly because of the superior system available at 6 cm, and partly because a detection at 5 GHz would more likely be accompanied by a detection at 1.4 GHz than vice versa. High frequency (5 GHz) Cnα lines are largely due to spontaneous emission from small regions

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Table 1. Sources from which Cnα lines were detected

Source	α (1950.0) h m s	δ ° ′ ″	line	T_A (°K)	ΔV_L (km s^{-1})	V_L (km s^{-1})	D (pc)	Remarks
NGC 2023	05 39 07	−02 16 58	C109α	0.035 ± 0.007	1.2 ± 0.2	10.2 ± 0.2	500	B1.5V, R52, IR, CO, RC, Cnα
			C109α	0.028 ± 0.007	1.3 + 0.2	11.1 ± 0.2		
NGC 2068	05 44 12	+00 02 54	C109α	0.020 ± 0.008	2.1 ± 0.4	10.8 ± 0.2	500	B2III, B3–5, IR, CO, RC, OH, Cnα
			S109α	0.012 ± 0.008	1.6 ± 0.5			
NGC 2071	05 44 33.9	+00 16 47	C109α	0.018 ± 0.007	1.6 ± 0.2	10.0 ± 0.2	500	B2–3, IR, OH, Cnα
			C166α	<0.055				
NGC 2170	06 05 05.6	−06 23 30	C109α	0.014 ± 0.006	3.9 ± 0.6	9.6 ± 0.3	830	B1, R67 (1 Mon R2)
			C166α	<0.055				
1 ρ Oph	16 22 22.5	−24 21 04	C109α	<0.024			160	B2V, R105, IR, CO, RC, Cnα
			C166α	0.05 ± 0.02	1.8 ± 0.3	3.4 ± 0.2		
			S166α	0.03 ± 0.02	0.6 ± 0.3			
2 ρ Oph	16 23 32.8	−24 16 48	C109α	0.136 ± 0.006	1.5 ± 0.05	3.46 ± 0.1	160	IR, CO, RC, Cnα
			S109α	0.017 ± 0.006	1.2 ± 0.3			
			C137β	0.046 ± 0.005	1.6 ± 0.1	3.45 ± 0.2		
			S137β	0.007 ± 0.005	1.5 ± 0.9			
	16 23 32.8	−24 14 48	C109α	0.16 ± 0.01	1.2 ± 0.07	3.5 ± 0.2		(offset 2′ north)
	16 23 32.8	−24 18 48	C109α	0.13 ± 0.02	1.7 ± 0.09	4.0 ± 0.2		(offset 2′ south)
	16 23 41.8	−24 16 48	C109α	0.09 ± 0.02	1.5 ± 0.2	3.8 ± 0.2		(offset 2′ east)
	16 23 23.9	−24 16 48	C109α	0.13 ± 0.01	1.3 ± 0.09	3.9 ± 0.2		(offset 2′ west)

The remarks column gives the following information about the source: star type (if visible); reflection nebula (RN), where possible from the catalogs of Racine (1968) and Herbst (1974, 1975) (e.g. R52, H17a); presence of infrared emission (IR-usually 2μ); presence of a CO, H_2CO peak or OH, H_2O maser; presence of a compact radio continuum source (RC); and previous detection of a carbon recombination lines (Cnα)

Table 2. Sources from which Cnα lines were not detected

Source	α (1950) h m s	δ ° ′ ″	line	T_A (°K)	D (pc)	Remarks
1 Ori R	05 38 24.3	−01 31 55	C109α	<0.018	600	B2V, R51
NGC 2071 (OH)	05 44 30.3	+00 20 18	C109α	<0.025	500	OH
			C166α	<0.055		
2 Mon R2	06 05 19.8	−06 22 40	C109α	<0.020	830	B0, OH, H_2O, RC
			C166α	<0.055		
3 Mon R2	06 05 37.4	−06 13 08	C109α	<0.038	830	B1.5V, R68
4 Mon R2	06 05 58.8	−05 19 51	C109α	<0.016	830	B1V, R70
C Ma R1	07 02 03.6	−10 22 44	C109α	<0.019	690	B0IV, R93
NGC 2626	08 34 00	−40 30 00	C109α	<0.015	950	B1V, H17a
NGC 3503	10 59 24	−59 35 00	C109α	<0.022	2600	B0V, B2V, H46a–d
1 Cham	11 05 21	−77 05 22	C109α	<0.023	115	RN, H_2CO
2 Cham	11 07 03	−77 22 13	C109α	<0.015	115	RN, H_2CO, IR
			C166α	<0.080		
3 Cham	11 07 26	−76 19 52	C109α	<0.030	115	RN, H_2CO, IR
1 Coalsack	12 28 42	−63 28 00	C109α	<0.025	170	RN, H_2CO, IR
2 Coalsack	12 27 24	−63 32 00	C109α	<0.025	170	RN, H_2CO, IR
1 Sco R1	15 55 49.3	−25 58 18	C109α	<0.019	145	B1V, B2V, R99
2 Sco R1	16 22 34.9	−23 20 00	C109α	<0.018	145	B2IV+V, R106
			C166α	<0.075		
3 ρ Oph	16 22 38.7	−24 19 40	C109α	<0.021	160	IR, CO
NGC 6193	16 35 24	−48 50 00	C109α	<0.024	1200	B1V, H72c
Sco R2	17 00 05.7	−51 00 46	C109α	<0.020	720	B2V, B3V, H81
1 R Cr A	18 58 19.5	−36 55 35	C109α	<0.019	200	B9, IR, CO
2 R Cr A	18 58 31.5	−37 01 21	C109α	<0.021	200	A5, IR, CO, RC
			C166α	<0.05		
3 R Cr A	18 58 50.0	−37 05 36	C109α	<0.023	200	CO, RC

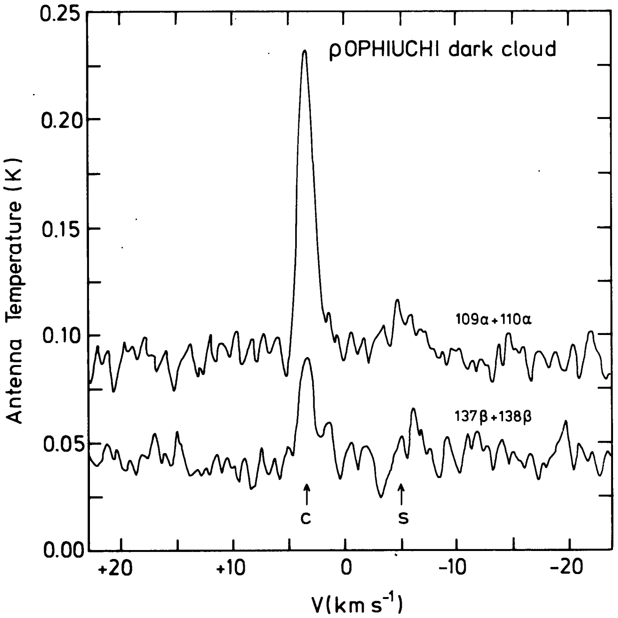

Fig. 1. 109α + 110α (top) and 137β + 138β (bottom) spectra of the source 2 ρ Oph. A linear baseline has been removed and the spectra have been Hanning smoothed; the velocity resolution is 0.47 km s^{-1}. The velocities of the carbon (C) and sulfur (S) lines are indicated by the arrows

(~1–5′) with large electron densities (~1–10 cm^{-3}), and there is a good chance that lower frequency lines will also be detectable from the same regions or surrounding envelopes, due partially to stimulated emission. On the other hand, many low frequency (1.4 GHz) Cnα lines may be due largely to stimulated emission from extended (10′–20′) regions of low electron density (~0.1–1 cm^{-3}), and high frequency emission from such regions would be very weak. With two frequencies available one can in principle solve for the physical parameters of the C II regions. The smaller beam at 5 GHz was not considered to be a disadvantage in this search, because the criteria mentioned above should identify the location of a likely C II region within a few arcmin.

The detections of carbon and sulfur lines are listed in Table 1, and upper limits are given in Table 2. Only in two cases (NGC 2023 and 2 ρ Oph) were lines detected with a high signal-to-noise ratio; the spectra for these two cases are shown in Figs. 1 and 2. The other possible detections are shown in Fig. 3; they must be considered marginal at best.

Interpretation

Rho Ophiuchus

The source 2 ρ Oph has been much studied by various workers; it is the brightest known source of carbon recombination line emission from dark clouds. Pankonin and Walmsley (1978a) have shown that the peak line emission is centred on the infrared source G35 (Grasdalen et al., 1973) and the weak thermal radio source BZ4 (Brown and Zuckerman, 1975); they conclude that the star G35 ionizes a small H II region (BZ4), heats a far infrared source (Fazio et al., 1976), and provides most if not all of the carbon ionizing photons.

We have measured the intensity of the C109α line in 5 positions centred on G35 (Table 1). In the central position we find a brightness temperature of 0.22 °K; Pankonin and Walmsley (1978a) using a 2′.6 beam obtained 0.35 °K. Comparison of these results yields an upper limit of ≈ 3′ for the effective size of the C109α core, consistent with the value of 2′ given by Pankonin and Walmsley. However, the line intensity does not fall off in the north–south direction (Table 1), indicating an angular size > 8′. From the core–halo model proposed by Pankonin and Walmsley we would expect line intensities a factor of five less than observed at the north and south offset positions; that model therefore does not adequately explain the observations.

The β/α ratio from Table 1 agrees with that measured by Pankonin and Walmsley (1978a). In addition we have a possible detection of S137β; the β/α ratio for sulfur is almost identical to that for carbon, indicating that the *observed* sulfur and carbon lines originate in similar regions.

The source 1 ρ Oph is located at the position of the B2–B3 star HD 147889; a weak radio continuum source, BZ3 (Brown and Zuckerman, 1975), is coincident. Low-frequency (~1.4 GHz) carbon recombination lines have been observed previously in this direction (Brown et al., 1974). Our detection of C166α emission is consistent with those earlier observations. We may also have detected a S166α line here; if so it appears to be another example of a region with low electron density and high sulfur to carbon ratio. The absence of detectable C109α line emission from this direction indicates that there is no compact C II core at the position of HD 147889. Intercomparison of the C158α and C166α line observations by Pankonin and Walmsley (1978a), Brown et al. (1974), and from Table 1 indicates a source size > 8′, electron density ≈ 0.5–1 cm^{-3}, and T_e ≈ 10–20 °K; a C II region with these parameters is consistent with our lack of detection of C109α.

NGC 2023

Our C109α, 110α spectrum of this source (Fig. 2) indicates that the two components identified by Pankonin and Walmsley (1976) at 10 km s^{-1} and 11 km s^{-1} are of roughly equal amplitude in our 4′ beam. Pankonin and Walmsley had found the 10 km s^{-1} component to be approximately twice as strong

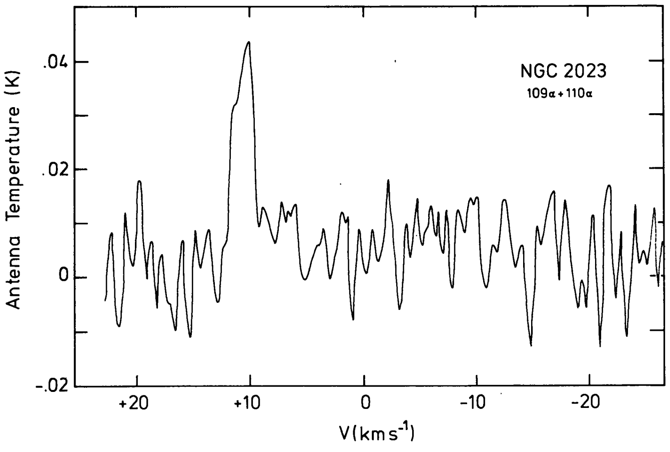

Fig. 2. 109α + 110α spectrum of the source NGC 2023. A linear baseline has been removed and the spectrum has been Hanning smoothed; the velocity resolution is 0.47 km s^{-1}

as the 11 km s^{-1} component in their 2′.6 beam (C110α). Our observations thus support their interpretation in terms of a compact (≈2′), dense 10 km s^{-1} component and a more extended (≳8′), lower-density 11 km s^{-1} component.

M78 – NGC 2068 *and* NGC 2071

In the same dust cloud as NGC 2023 (L1630) but 2.5 degrees to the northeast is the M78 complex, which consists of the reflection nebulae NGC 2068 and NGC 2071. Figure 3 shows possible detections of C109α from both nebulae, and of S109α from NGC 2068. Brown et al. (1976) have detected C166α and C142α from NGC 2068, and Pankonin and Walmsley (1978b) have detected C158α and S158α from NGC 2068 and C157α from NGC 2071. Upper limits for C110α emission from both nebulae by Pankonin and Walmsley (1978b) are consistent with our possible detections. In all cases the radial velocities agree within the errors.

A comparison of the intensities of the C158α and C166α lines measured with different beams (8′ and 23′) yields a rough angular size of ~15′ for the C II region in NGC 2068. A direct comparison of the 158α and 109α line intensities (both observed with beams much smaller than the source) can then be made, to estimate the electron density; the result is ≈0.2 or 1 cm^{-3} for both carbon and sulfur, assuming electron temperatures of 20 and 50 °K respectively.

In the case of NGC 2071 the angular size of the C II region is unknown, although the C158α observations by Pankonin and Walmsley (1978b) indicate that it is extended at least in the direction of NGC 2068. Our upper limit for C166α is in conflict with the C157α detection by Pankonin and Walmsley unless the C II region is smaller than ~20′. The intensity ratio C109α/C157α is about the same as that for NGC 2068.

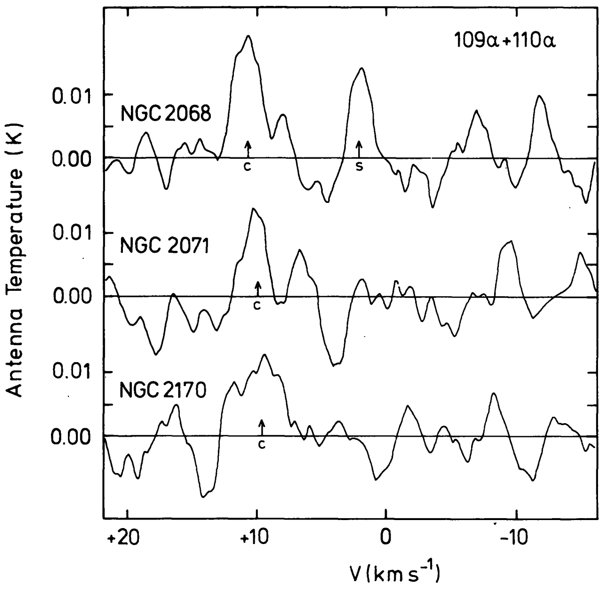

Fig. 3. 109α + 110α spectra of the sources NGC 2068, NGC 2071, and 1 Mon R2. Linear baselines have been removed and the spectra have been Hanning smoothed; the velocity resolution is 0.47 km s^{-1}. The velocities of the possible carbon (C) and sulfur (S) lines are indicated by the arrows

NGC 2170

This reflection nebula has been studied optically by van den Bergh (1966) and Racine (1968). It lies in the Mon R2 association of reflection nebulae. Radio line and continuum observations of the region have been published by Downes et al. (1975). NGC 2170 may be associated with the B1 star BD-61415. Figure 3 shows a possible detection of a C109α line from NGC 2170. The radial velocity (+9.6 km s^{-1}) is consistent with values obtained from H I and molecular lines (≈8–12 km s^{-1}).

The nearby source 2 Mon R2 is the strong radio source G213.7–12.6, thought to be a compact H II region embedded deep within a dense dusty molecular cloud (Downes et al., 1975). The C110α line has been detected by Downes et al. (1976). The observed antenna temperature of 0.07 ± 0.01 °K as measured with the 2′.6 beam of Effelsberg (Downes, private communication) is consistent with our upper limit provided that the size of the emitting region is much smaller than 2′.6. This suggests that the line mostly arises in the 15″ main source and not in the extended envelope of 2′ (Downes et al., 1975). The same applies to the H110α line, for which we measure an antenna temperature of $T_A = 0.125$ °K and Effelsberg $T_A \approx 0.36$ °K.

Conclusions

The most striking result of these observations is the large number of non-detections. The limits are nearly an order of magnitude below the strength of the strongest line detected. In all cases we pointed at some carefully specified position, usually that of a reflection nebula with an embedded early B-type star; it was no random search. The non-detections could be due to a variety of causes, including: (1) the geometry of the source-dilution of the stellar radiation; (2) low electron density; (3) competition for carbon-ionizing photons by dust; (4) depletion of carbon; and (5) for the more distant sources, possible beam dilution.

In any case, sources like 2 ρ Oph and NGC 2023 are clearly rare. Our survey was aimed at sources of that type – relatively dense, compact C II regions which would be readily detectable at both high and low frequencies. From all available observation of Cnα lines, it now seems likely that extended C II regions of low electron density are more plentiful than compact regions, and these would show up most strongly at low frequencies. Thus it appears that searches for carbon recombination lines from dark clouds are best done at frequencies near 1 GHz; indeed at such frequencies it is even possible to detect carbon recombination lines from diffuse interstellar clouds (Crutcher, 1977).

It should be noted that while detectable carbon recombination line emission may imply the presence of embedded early-type stars, the converse is not necessarily true, as there are many factors which affect the strength of the lines. Thus, searching for carbon recombination lines may not be the most efficient way of searching for embedded stars. The weakness of most carbon lines furthermore means that it is at present impossible to determine the physical parameters of these C II regions with any precision. Order-of-magnitude estimates of temperature and density are possible, but the achievement of greater accuracy will require lower-noise receivers. However, careful mapping of the few regions that can be studied in detail may give useful information on the chemistry of the clouds.

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References

Bergh, S. van den: 1966, *Astron. J.* **71**, 990
Brown, R. L., Gammon, R. H., Knapp, G. R., Balick, B.: 1974, *Astrophys. J.* **192**, 607
Brown, R. L., Knapp, G. R.: 1974, *Astrophys. J.* **189**, 253
Brown, R. L., Knapp, G. R., Kuiper, T. B. H., Kuiper, E. N. R.: 1975, *Astrophys. J. Letters* **195**, L23
Brown, R. L., Zuckerman, B.: 1975, *Astrophys. J. Letters* **202**, L125
Cesarsky, D. A., Encrenaz, P. J., Falgarone, E. G., Lazareff, B., Lanqué, R., Lucas, R., Weliachew, L.: 1976, *Astron. Astrophys.* **48**, L167
Chaisson, E. J.: 1975, *Astrophys. J. Letters* **197**, L65
Crutcher, R. M.: 1977, *Astrophys. J. Letters* **217**, L109
Downes, D., Winnberg, A., Goss, W. M., Johansson, L. E. B.: 1975, *Astron. Astrophys.* **44**, 243
Downes, D., Wilson, T. L., Bieging, J., Winnberg, A.: 1976, *Mitteil. Astron. Ges.* **40**, 132
Falgarone, E. G., Cesarsky, D. A., Encrenaz, P. J., Lucas, R.: 1978, *Astron. Astrophys.* **65**, L13
Fazio, G. G., Wright, E. L., Zeilik II, M., Low, F. J.: 1976, *Astrophys. J. Letters* **206**, L165
Gordon, M. A.: 1973, *Astrophys. J.* **184**, 77
Grasdalen, G. L., Strom, K. M., Strom, S. E.: 1973, *Astrophys. J. Letters* **184**, L53
Herbst, W.: 1974, *Astron J.* **79**, 941
Herbst, W.: 1975, *Astron. J.* **80**, 212, 498, 503, 683
Johansson, L. E. B., Höglund, B., Winnberg, A., Nguyen-Q-Rieu, Goss, W. M.: 1974, *Astrophys. J.* **189**, 455
Knapp, G. R., Brown, R. L., Kuiper, T. B. H.: 1975, *Astrophys. J.* **196**, 167
Knapp, G. R., Brown, R. L., Kuiper, T. B. H., Kaler, R. K.: 1976, *Astrophys. J.* **204**, 781
Knapp, G. R., Kuiper, T. B. H., Brown, R. L.: 1976, *Astrophys. J.* **206**, 109
Pankonin, V., Walmsley, C. M.: 1976, *Astron. Astrophys.* **48**, 341
Pankonin, V., Winnberg, A., Booth, R. S.: 1977, *Astron. Astrophys.* **58**, L25
Pankonin, V., Walmsley, C. M.: 1978a, *Astron. Astrophys.* **64**, 333
Pankonin, V., Walmsley, C. M.: 1978b, *Astron. Astrophys.* **67**, 129
Racine, R.: 1968, *Astron. J.* **73**, 233.