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New peculiar CO data of the shell around IRC +10 216

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Abstract. A CO(1-0) on-source spectrum of the well-known carbon star IRC +10 216 taken with the IRAM 30m telescope in June 1996 shows excess emission between –18.3 and –14.3 km s^{-1} at the red wing of the underlying profile. The excess emission is confirmed in January 1997 but is absent in April 1997 and June 1998 IRAM spectra. Such a transient feature has not been seen before in this star or any other AGB star. In April 1997 we mapped the circumstellar shell out to 110″. Both the J = 1-0 and J = 2-1 spectra show "spikes" or components which vary in strength with position in the envelope. One of these components corresponds to the velocity interval mentioned above. An immediate conclusion is that the circumstellar shell is not spherically symmetric, contrary to what was believed based on lower spectral resolution data. We are probably seeing emission from a complex geometrical structure. Neither a disk structure nor a double-wind structure seem to be able to explain the observations. The on-source transient behaviour of the red excess emission can reasonably well be explained by a single large ($\sim 5 \times 10^{13}$ cm) blob, that expands due to internal motion.

Key words: circumstellar matter – stars: individual: IRC +10 216 – mass loss – AGB – radio lines: stars

1. Introduction

IRC +10 216 (= AFGL 1381 = CW Leo) is often considered the prototype infrared carbon star. It is a carbon Mira with a period of 649 days (Le Bertre 1992) and of considerable apparent brightness. It is luminous, about 10 000 $L_\odot$ following the period-luminosity relation of Groenewegen & Whitelock (1996), and at a distance of about 135 pc (e.g. Le Bertre 1997, Groenewegen et al. 1998). It is a well-known calibration object, in particular for molecular line emission observations (e.g. Mauersberger et al. 1989).

Here we report on excess emission seen in a CO(1-0) spectrum taken on 25 June 1996 with the IRAM telescope, and confirmed by later observations. We present a map of the circumstellar shell at high velocity resolution. We compare the results to previous CO observations.

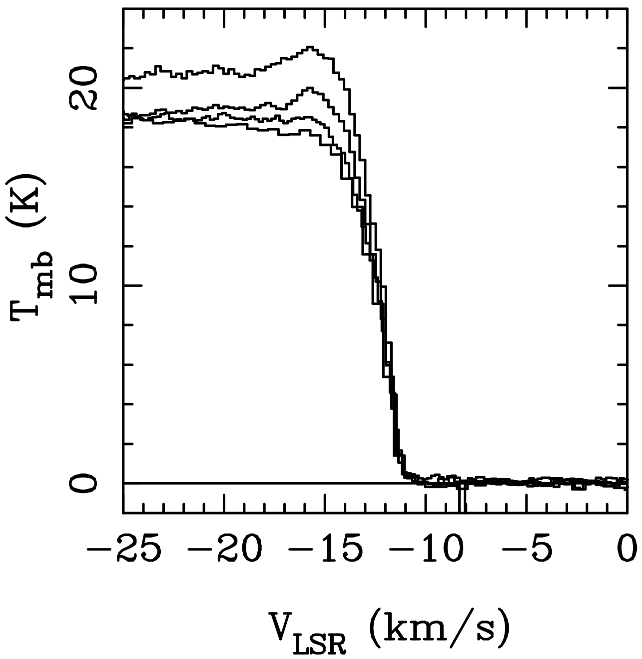

Fig. 1. Red part of the CO J = 1-0 spectrum. From top to bottom June 1996, January 1997 (both at 100 KHz resolution), April 1997 spectrum at 78 KHz resolution, June 1998 (at 200 KHz resolution). The rms noise is better than 0.17 K. The June 1998 spectrum has been multiplied with a factor of 0.91 for clarity. The others are calibrated spectra as observed.

2. The observations

The IRAM observations were obtained on June 25, 1996 (observer HGL), January 15-16, 1997 (observer MG), April 3-4, 1997 (observer MG) and June 3-4, 1998 (observer MG). On the

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first two occasions the instrumental set-up was identical. Two 1.3mm SIS receivers and two 3.0mm SIS receivers (measuring the different polarizations) were used simultaneously and tuned to the CO(1-0) and CO(2-1) lines. The 100 KHz backend was connected to one of the 3mm receivers, resulting in a velocity separation per channel of 0.26 km s^{-1}. The 1MHz backend was split in two and connected to the two 1.3mm receivers, resulting in a velocity separation of 1.3 km s^{-1}. The autocorrelator was split into two and connected to the two 1.3mm receivers resulting in a velocity separation of 0.81 km s^{-1}. In April 1997 the set-up was as follows: the two 3mm receivers were tuned to the CO (1-0) and the HCN(1-0) line, while the 1.3mm receiver was tuned to the CO (2-1) line. The 1MHz backend was used to observe the HCN line (channel separation of 3.38 km s^{-1}). The autocorrelator was split to observe the CO (1-0) line at a resolution of 78 KHz (0.20 km s^{-1}), and the J = 2-1 line at 312 KHz resolution (or 0.41 km s^{-1}). In June 1998 the set-up was as on the first two epochs using the 1MHz backend and the autocorrelator.

IRC +10 216 was observed on two consecutive occasions on June 25, 1996 and seven times between January 15-16, 1997 in the course of another project as calibration observations on both occasions. In April 1997 we mapped the star out to a radial off-set of about 110″ in the CO (1-0), CO (2-1) and HCN (1-0) lines. In June 1998 the star was observed once for calibration purposes on another project.

The high-resolution spectra of the J = 1-0 line are shown in Fig. 1. The blue part is missing in the June 1996 and January 1997 observations due to the limited number of channels of the backend and because we did not center it on the line. The June 1996 profile shows excess emission between –18.3 and –14.3 km s^{-1}. A technical defect can be ruled out as the emission is visible in all six spectra taken with different receivers and different backends. In January 1997 we also checked that the emission was still present if we disconnected one of the 3mm and 1.3mm receivers, and the corresponding backend. An interference is very unlikely as this affects mostly one channel while the excess emission is several km s^{-1} wide. In June 1996, the peak temperature[1] of the excess emission is 1.2 K with respect to the underlying plateau and has an integrated intensity of 2.4 K km s^{-1}. The integrated intensity of the entire CO (1-0) lines as measured with the autocorrelator is 544 K km s^{-1}. In January 1997, the total integrated intensity was 505 K km s^{-1}, the excess emission in the velocity interval between –18.4 and –14.3 km s^{-1} was 1.7 K km s^{-1}, and the peak was 1.6 K higher than the line center. It is also clear that even at bluer velocities the intensity is less, rising towards the red. This is particularly clear when compared to the April 1997 observation when the 1-0 profile was flat-topped again and the excess emission has disappeared. In June 1998 this corresponds even to a "lack" of emission with respect to the flat-topped profile.

[1] The temperature scale in this paper is mean-beam brightness temperature.

Table 1. Data of spectra discussed

Obs. date	J =	Δv (km/s)	r.m.s. (K)	time (min.)	phase ϕ
September 1988	1-0	2.60	0.050	20	0.90
	2-1	1.30	0.088	20	
7-10 August 1991	1-0	2.60	0.03	10	0.47
	2-1	2.60	0.06	10	
23-29 December 1994	1-0	0.81	0.15	3	0.44
	2-1	0.41	0.18	3	
25-28 January 1995	1-0	0.81	0.051	20	0.49
	2-1	1.30	0.055	20	
28 May 1996	1-0	0.81	0.21	1	0.25
	2-1	0.41	0.39	3	
23 June 1996	2-1	0.20	0.29	8	0.28
25 June 1996	1-0	0.26	0.14	4	0.28
	1-0	0.81	0.072	8	
	2-1	1.30	0.11	8	
15-16 January 1997	1-0	0.26	0.17	16	0.59
	1-0	0.81	0.060	35	
	2-1	1.30	0.052	35	
3-4 April 1997	1-0	0.20	0.12	25	0.71
	2-1	0.41	0.13	25	
	1-0	3.38	0.20	25	HCN
3-4 June 1998	1-0	0.52	0.15	7	0.37
	1-0	0.81	0.14	7	
	2-1	1.30	0.16	14	

Listed are the date of the observing run, transition, channel spacing in km s^{-1}, rms noise, integration time and phase in the light curve.

3. Comparison with other spectra

IRC +10 216 is an important millimetre line calibrator and therefore many spectra taken with different telescopes over a long time span are published in the literature; a compilation up to September 1992 can be found in Loup et al. (1993). Also one of us (MG), with different collaborators, has observed this star many times. As these spectra are readily available we will concentrate on comparing these spectra to the new data. In addition, Dr. Truong-Bach (Observatoire de Paris-Meudon) made his mapping data available described in Truong-Bach et al. (1991), Dr. J. Kastner (MIT) who observed IRC +10 216 at IRAM in May 1996 made his high resolution J = 1-0 and 2-1 spectra available, and Dr. C. Thum (IRAM Grenoble) who was the observer before us in June 1996 kindly made his high resolution J = 2-1 spectrum available.

Table 1 contains information on the spectra discussed in this paper regarding observation dates, channel spacing, rms noise, integration times and phase ϕ in the light curve, based on a period of 649 days and maximum light (ϕ = 0) at JD = 2447483 (Le Bertre 1992).

The CO J = 1-0 and 2-1 spectra are shown in Fig. 2, offsetted from each other for clarity. We first discuss the J = 1-0 line. The temperature at the line center of the IRAM spectra varies between about 18 and 24 K. This is within the normally quoted absolute calibration errors.

The shapes are all very similar with the exception that the June 1996 and January 1997 spectra clearly show the excess

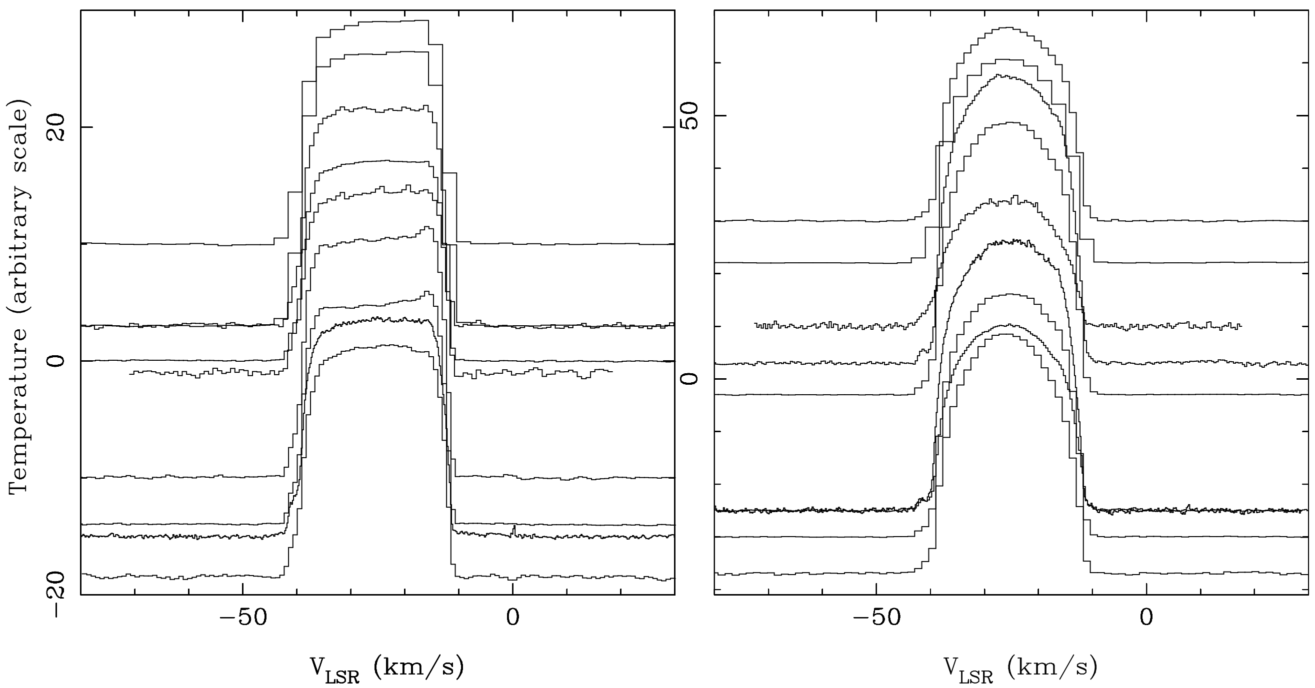

Fig. 2. Time sequence of available IRAM J = 1-0 (left hand) and J = 2-1 (right hand) spectra. From top to bottom Sep. 1988, Aug. 1991, Dec. 1994, Jan. 1995, May 1996, June 1996, Jan. 1997, April 1997, June 1998. Spectra are off-setted from each other.

emission near the red wing of the profile as discussed before. Other published IRAM 1-0 profiles [Bujarrabal et al. 1986 (observation date June 1985; $\phi \sim 0.07$) and Kahane et al. 1992 (observation date August 1988; $\phi \sim 0.86$)] are also all flat-topped with no evidence for excess emission.

Regarding the J = 2-1 transition, there is no obvious evidence for excess emission in the June 23 spectrum, nor in the lower resolution June 25 spectrum, which is not shown here. To investigate the matter further we present in Fig. 3 the difference spectra (May 1996 - December 1994), (June 23, 1996 - December 1994) and (April 1997 - December 1994), where we first adjusted the December 1994 spectrum to the same absolute temperature as the spectrum from which it is subtracted. Evidence for excess emission is clearly seen between –23 and –15 km s^{-1} at a significant level in the June 1996 difference spectrum, which is absent on the other two occasions. Furthermore, there are features at –12 and –39 km s^{-1} in all three difference spectra which indicate variations in the wings of the J = 2-1 line profiles, possibly due to variations in the expansion velocity, or small velocity shifts in the spectra due to optical depth effects.

We may conclude that the red excess emission was also present in the J = 2-1 line in June 1996, but this is less clear and convincing than in the J = 1-0 spectra. The reason is that the velocity interval where the excess occurs, lies on the steep wing of the 2-1 profile but on the essentially flat-topped 1-0 profile, and therefore is easier to detect. In a way we are fortunate that the combination of source size of the CO (1-0) emission and the beam size of the IRAM telescope at that frequency result in a flat-topped profile.

4. The mapping data

In April 1997 we mapped IRC +10 216 out to a distance of about 110$''$ in the CO (1-0), CO (2-1) and HCN (1-0) lines. The only other published IRAM CO map of this object is by Truong-Bach et al. (1991) who mapped the star out to 54$''$ at 1 MHz spectral resolution. Our CO map was obtained at 78 KHz and 312 KHz resolution.

The on-source spectra are shown in Figs. 4 (CO J = 1-0), 5 (CO J = 2-1) and 6 (HCN 1-0). Some of the spectra at large radial off-sets are smoothened. The CO spectra are normalised so they appear equally strong. The absolute scale can be estimated from the zero intensity level, which is –0.3 K in all plots.

The off-set spectra in CO are remarkable, in the sense that the profiles are not smooth but show distinct components. This has never been seen before in this, or any other, AGB star. The HCN map does not show this behaviour. This is at least partly due to the much lower velocity resolution, which is probably also the reason why Truong-Bach et al. (1991) did not see these components in their CO spectra (see below).

One can identify components between approximately –18 and –14 km s^{-1} (strikingly similar in velocity to the excess emission seen in June 1996 and January 1997), –40 and –34 km s^{-1}, –34 and –22 km s^{-1}. The exact velocities seem to change slightly with position. The relative strength of these components changes dramatically with position. On the other hand, there is good correspondence between the components in the 1-0 and 2-1 profiles at a given off-set position.

We have made contour plots of the integrated intensity for different velocity intervals. Because the step size in the map is

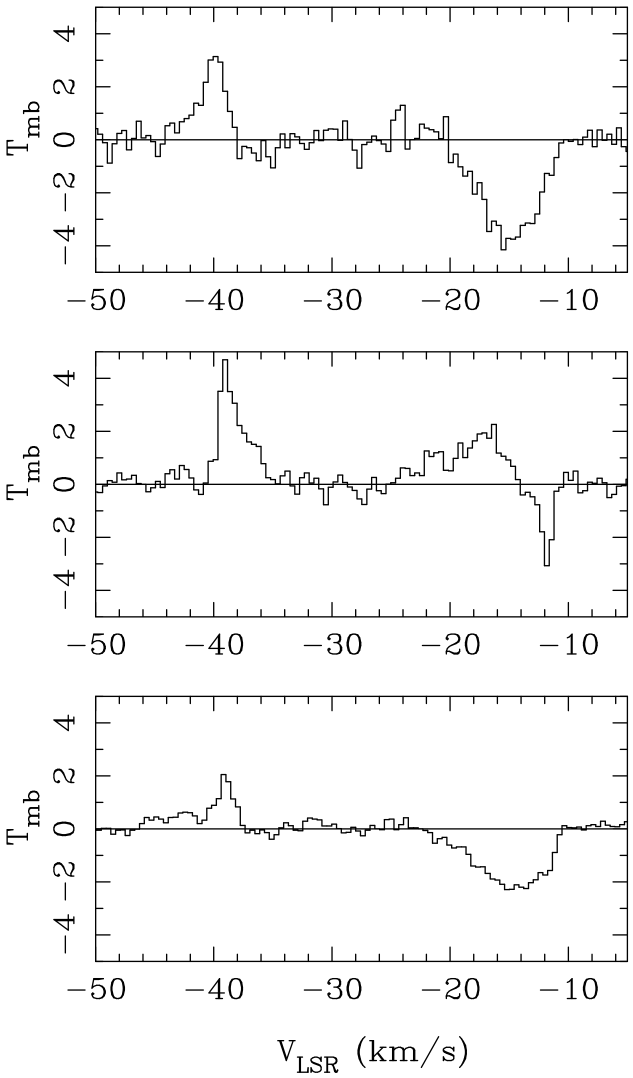

Fig. 3. Difference between J = 2-1 spectra taken on 28 May 1996 and December 1994 (top), between 23 June 1996 and December 1994 (middle) and between April 1997 and December 1994 (bottom) at 0.4 km s^{-1} channel spacing. The December 1994 spectrum was scaled in each case before subtraction.

larger than the size of the beam this analysis is inconclusive as to tell whether different velocity bins peak at different positions. However, the peak of the emission is not at the central position but slightly to the north (see below as well).

Our data and that by Truong-Bach et al. (1991) are taken 8.5 years apart with the same telescope and it is interesting to compare the two data sets. In their Fig. 3 they plot the 1-0 and 2-1 profiles at 0, 6, 12, 24, 36 and 54″ off-set, averaged over the north, east, south west position. We have done the same for our spectra at 10, 30 and 36″ off-set, to compare to their spectra at 12, 36 and 54″ off-set. We have resampled our data to their 1 MHz resolution. The two data sets are compared in Fig. 7. Represented in this way, it is clear that the two datasets are indistinguishable. This implies that these phenomena *could* have been present at that time as well.

From Fig. 6 it is clear that the peak of the HCN integrated intensity is not at the central position. From a contour plot of the integrated intensity we estimate it to be at (+5″, +10″). The emission is elongated as well with a position angle of about 45°. This is contrary to the previous interferometric observations of Bieging et al. (1984) and Dayal et al. (1995), where the HCN emission is centered on the central position, and approximately spherical. A pointing error seems very unlikely, as the pointing was checked regularly on the same nearby pointing source, and the rms errors in the pointing model were of order 3″ only.

5. Discussion

We have discovered two – probably related – new and interesting features in the prototype infrared carbon star IRC +10 216: a transient emission feature in the red wing of the CO 1-0 profile (also present but less clear in the 2-1 profile), and different emission components in both 1-0 and 2-1 profiles throughout the envelope.

Although these observations speak for themselves, the interpretation of these phenomena is less straightforward. One firm conclusion is that the circumstellar CO shell is not spherically symmetric.

Asymmetries close to the star on a scale of 0.1-0.2″ were known previously from infrared observations (see Weigelt et al. 1998, Haniff & Buscher 1998 for the latest on this) but we now show that there exist asymmetries throughout the envelope.

Let us first point out that the original discovery of the excess emission in the on-source spectrum, as well as the later notion of features in the off-set spectra could only have been discovered thanks to the high velocity resolution (of order 100 KHz or better). As we demonstrated by comparing our resampled data to the map of Truong-Bach et al. (1991), a resolution of 1 MHz is insufficient to detect these features.

A second point to note is that an observer who uses IRC +10 216 as a calibration object, but has little or no experience or interest in the CO spectra of carbon stars as such, would perhaps not note or care that a CO 1-0 spectrum showed some small changes with respect to the calibration spectrum. In order words, it might well be that this feature has been observed before, but went unnoticed. It might therefore be worthwhile to look at archival data (in particular high resolution CO 1-0 spectra) taken with various telescopes. Published higher-J CO data (e.g. compilation in Groenewegen et al. 1998) do not seem to show this feature.

One question that might be addressed if such features where to be found in archival data, is the recurrence time scale of these phenomenon. Was its presence in the on-source spectra, that started between May and June 1996, and ended between

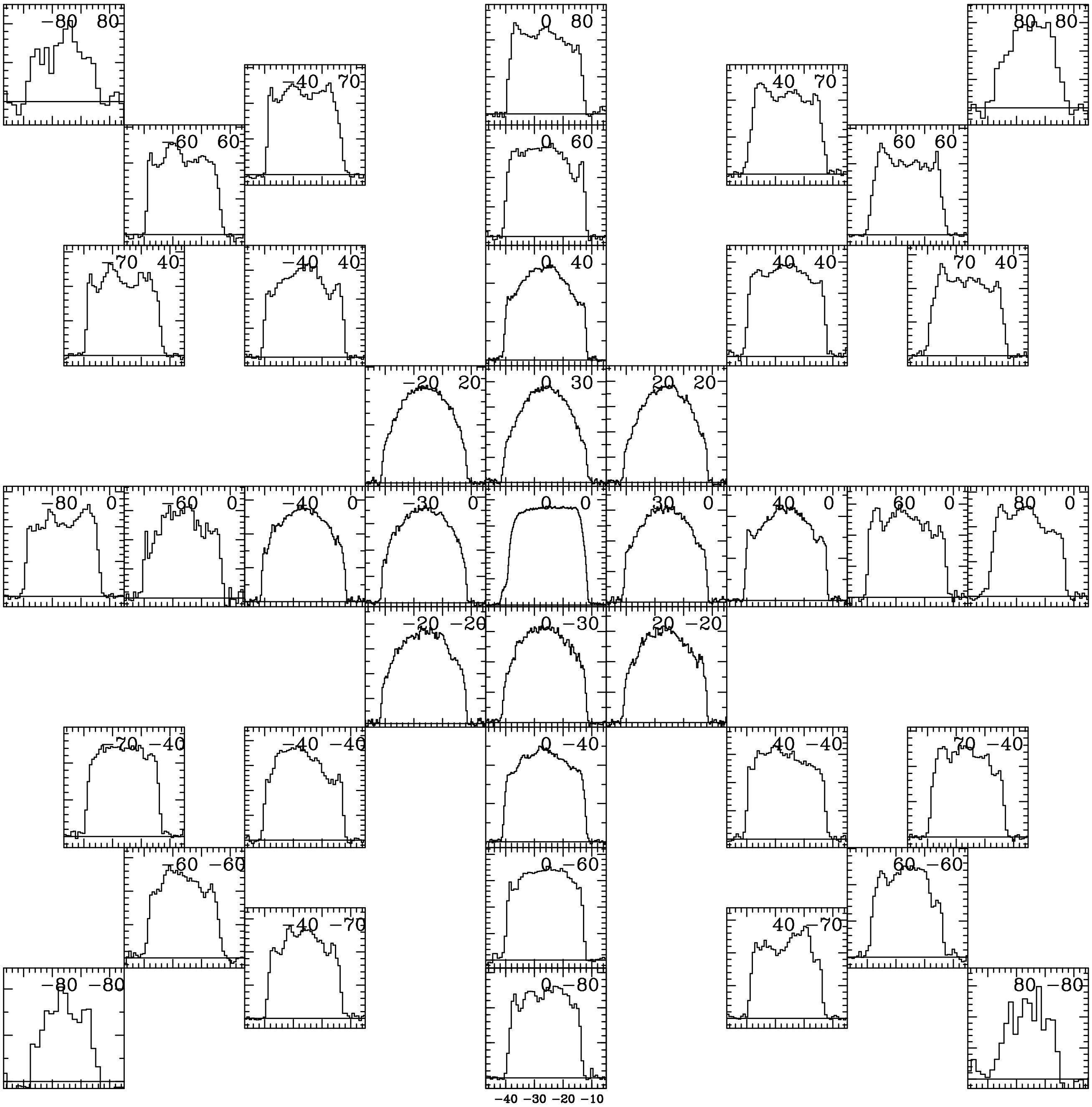

Fig. 4. CO 1-0 map. Offsets are indicated in each panel. All spectra are normalised, to better illustrate the different components. The lower temperature limit plotted is –0.3 K in all cases. The velocity range shown is between –47 and –5 km s^{-1}. North is up, East to the right.

January 1997 and April 1997, unique ? This is a time span of between 7 and 11 months, compared to the pulsation period of about 21 months. Could there be a connection ? On the other hand, if this phenomenon is connected to pulsation and would occur every cycle for 30-50% of the time, then it seems improbable that it has never been seen before, even considering the biases discussed above against observing such a phenomenon.

If something came in and out the line of sight, this would imply it has traversed roughly the full width of the beam ($21''$) in 7-11 months. At a distance of 135 pc, this corresponds to a traverse motion of 15-23 $\times$ 10^3 km s^{-1}, improbably high.

One of the first things that comes to mind to explain the mapping data is a geometrical one, for example a disk, or a “shell with evacuated holes” (Sloan & Egan 1995), as for example visualised in Dyck et al. (1987; their Fig. 7 which was

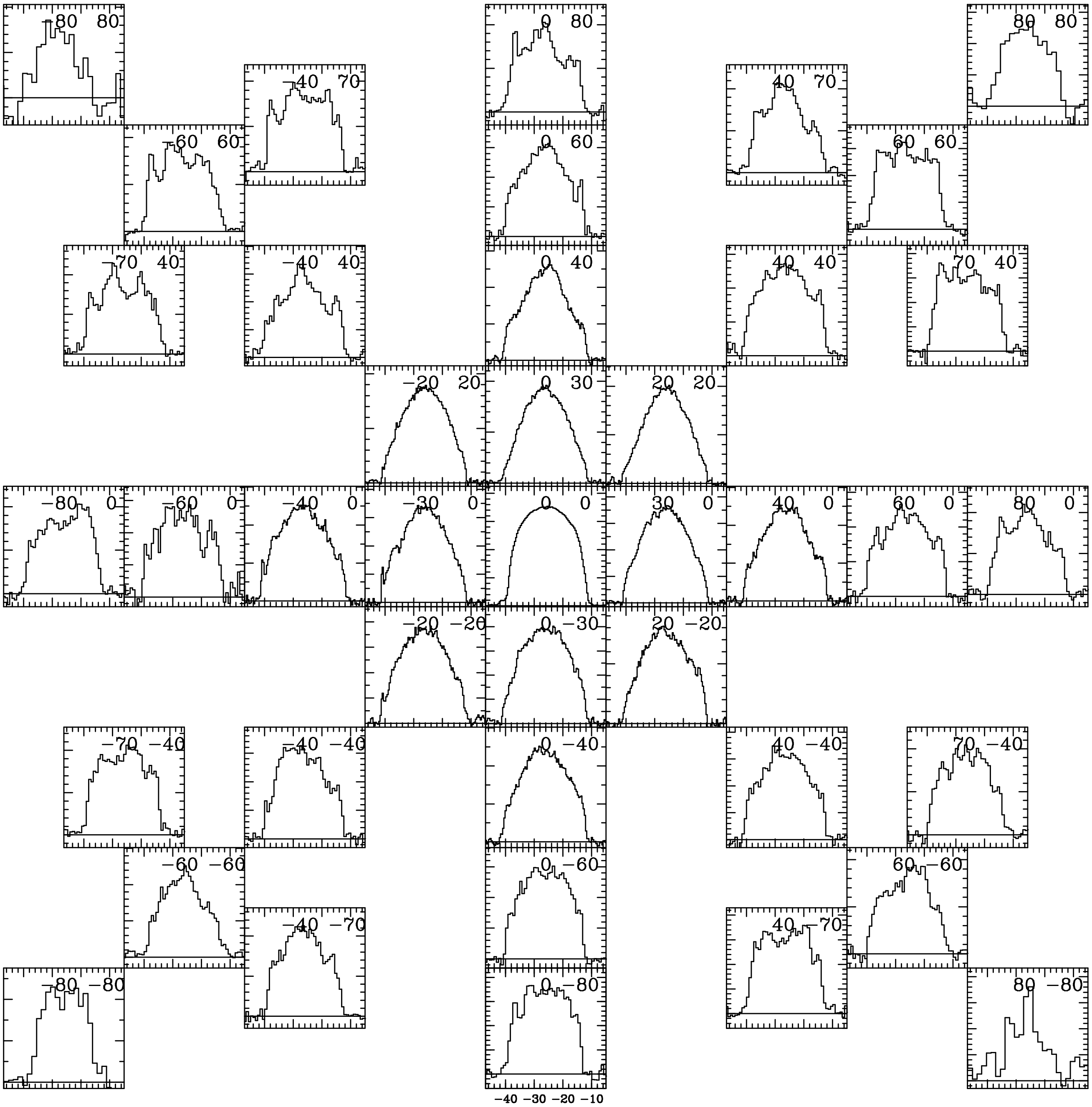

Fig. 5. CO 2-1 map. As Figure 4.

based to explain various observations on a scale of a few arc seconds, much smaller than the scale we are considering now). However, in such a schematic picture (assuming a disk with an uniform outflow and no angle dependence of the emission) one expects point symmetry of the excess emission around the central position of the red and blue-shifted emission. This is clearly not the case.

Knapp et al. (1998) present evidence of two winds with different velocities in several AGB stars. They observed J = 2-1 and 3-2 spectra at high velocity resolution. In particular the J = 3-2 spectrum of R Leo is qualitatively similar to our on-source J = 1-0 spectrum of IRC +10 216, having red excess emission. This is in contrast to their other examples (e.g. IRC +50 049, X Her [also see Kahane & Jura 1996], EP Aqr), where the two winds can be seen symmetrically w.r.t. the stellar velocity at both blue and red shifted velocities.

So, neither of these simple explanations seem to apply to our observations. Although the explanation of the present observations probably lies in a geometrical one, we can not constrain

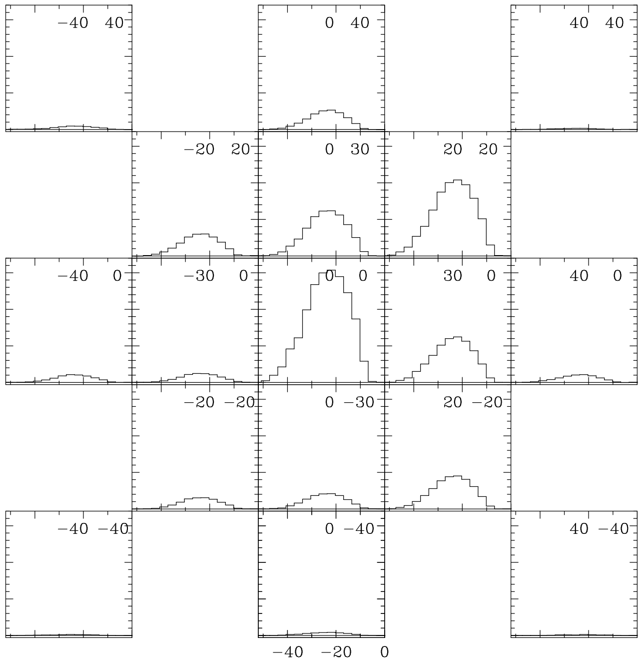

Fig. 6. HCN 1-0 map. The velocity range plotted is between –52 and –0 km s^{-1}, while the intensity is between –0.3 and 17 K. North is up, East to the right.

this geometry at present. Additional mapping data in the inner part at a higher spatial resolution and archival (on-source) data will be of help.

We will now focus on the transient behaviour of the red excess emission in the on-source spectrum. To pursue to idea of a clump ejected by the star, consider the following. Solving the radiative transfer equation, and assuming optically thin emission, and an excitation temperature much larger than the cosmic background temperature, one can derive the following expression between column density and integrated emission (e.g. Johansson et al. 1984):

$$\frac{N_l}{g_l} = \frac{1.67 \times 10^{14}}{\nu\, \mu^2\, S} \int T_{\rm mb}\, dv, \tag{1}$$

with ν in GHz, μ the permanent dipole moment (in Debye), the integrated intensity in K km s^{-1}, S the line strength which is equal to the J-number of the upper level in the case of CO and N_l and g_l the column density and statistical weight of the lower level. Furthermore, under the assumption of LTE, one has

$$\frac{N_l}{g_l} = \frac{N_{\rm tot}}{Q(T_{\rm ex})} \exp(-E_l/kT_{\rm ex}), \tag{2}$$

with Q the partition function, and $N_{\rm tot}$ the total column density. For excitation temperatures for the CO(1-0) line between 15 and 50 K, assuming an abundance ratio of CO-to-H_2 of 1.1 $\times 10^{-3}$ (Groenewegen et al. 1998), one then finds within a factor of 2 that

$$N_{\rm H_2} = 1.1 \times 10^{18} \int T_{\rm mb}(1-0)\, dv \qquad {\rm cm}^{-2}. \tag{3}$$

If the tempereture is higher than 10-50 K, the column density goes up; for example, for $T_{\rm ex}$ = 80 K the factor in front would be 3.2 $\times$ 10^{18}.

The largest blob identified in the Weigelt et al. (1998) paper has a radius of about 30 milli-arcseconds which, at 135 pc, corresponds to a linear size of 5 $\times$ 10^{13} cm. This is indeed somewhat larger than the typical blob sizes considered (Olofsson 1994, Olofsson et al. 1996). Recalling that in June 1996 the excess emission had an CO(1-0) integrated intensity of 2.4 K km s^{-1}, and combining all this, one finds that the density in such a single large blob is 5.2 $\times$ 10^4 H_2/cm^3. Since the blob size (60 mas diameter) is much smaller than the beam size (22$''$ FWHM), and Eq. (1) assumes that the source size is comparable to the beam size, this estimate is likely to be too low by a factor $(22000/60)^2 \approx 1.3 \times 10^5$. This then would lead to a density estimate of $\sim 7 \times 10^9$ cm^{-3} within a factor of a few. This is similar to the estimate by Olofsson (1994) of 10^{10} cm^{-3} based on SiO maser spots. The mass is this blob would be 8 $\times$ 10^{-6} $M_\odot$ allowing for 10% helium.

A distance of 10^{14} cm is crossed in 2.2 years at the expansion velocity of 14.5 km s^{-1}. With an underlying average mass loss rate of about 1.8×10^{-5} $M_\odot$yr^{-1} (e.g. Groenewegen et al. 1998) there would be enough mass available to form such a single big blob. This "quantitative estimate" shows that is it possible that a single large blob (possibly only rarely formed) is responsible for the excess emission. If one entertains the possibility of blobs further, and notices that an integrated emission which is about a factor of 5 smaller than the 2.4 K km s^{-1} in June 1996 would not have been detected, one can conclude that a similar phenomenon but now a mass ejection in the form of 100 clumps of size 10^{13} cm in random directions probably would have little observational consequences. The same goes for even more clumps of smaller size.

The excess emission at the red wing implies that the blob is moving away from us. Its sudden appearance could then be related to the fact that the blob was previously occulted by the central star. The fact that the excess emission disappeared again could either mean that the blob moved again behind the star or that the column density decreased. The former possibility is unlikely as it requires a non-radial motion and implies velocity shifts which are not readily seen in the spectra obtained at later dates. The latter possibility seems physically more attractive. The width of about 4 km s^{-1} in the excess emission in June 1996 already implies that there is some differential expansion or turbulent motion. Over a period of 10 months and with a differential velocity of 4 km s^{-1} the blob would be of size 6×10^{13} cm, and hence the column density would have decreased by about 45%. This would be too little to explain the observations which might indicate higher internal motions, or that the big blob broke up into smaller blobs following slightly different trajectories.

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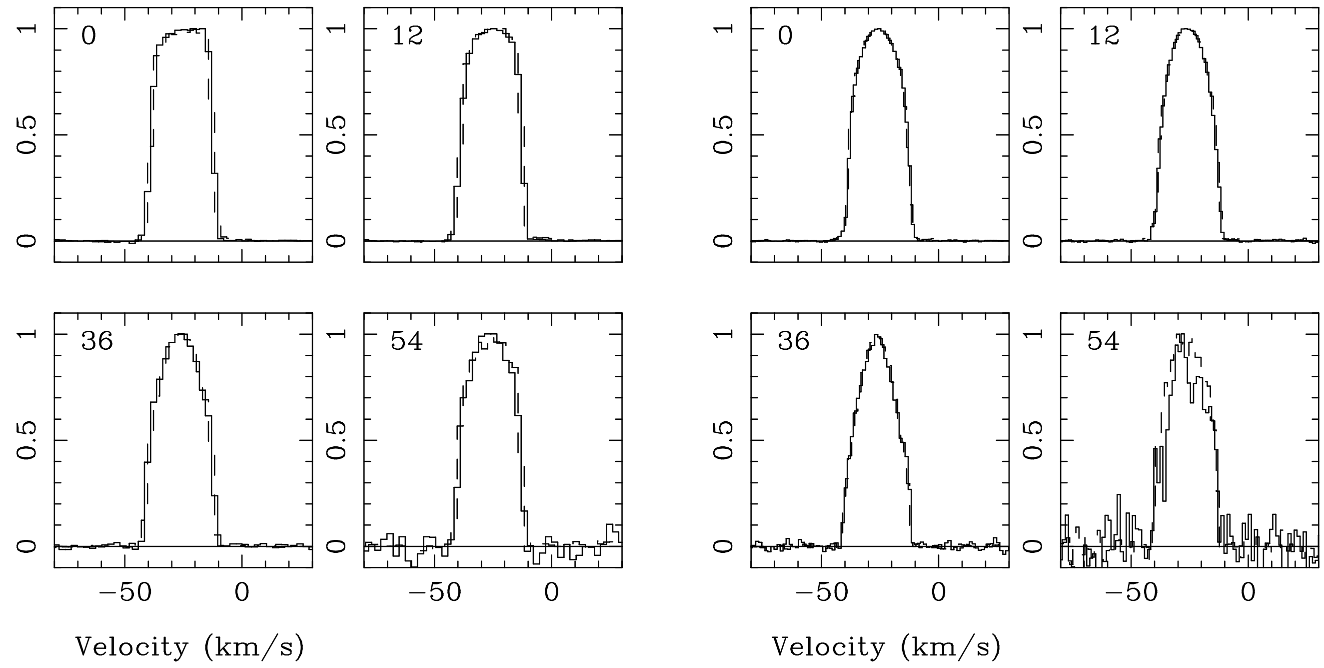

Fig. 7. A comparison between our data (dashed line) and that of Truong-Bach et al. (1991; solid line), averaged over N,E,S,W positions at the (approximate) off-sets indicated in the panels for the J = 1-0 (left hand side) and J = 2-1 (right hand side). Our data has been smoothened to their spectral resolution, and both datasets are normalised. The datasets are taken 8.5 years apart, and represented in this way, are indistinguishable.

Paris-Meudon) for his 1991 data and Wolfgang Wild (IRAM Grenada) for helpful comments. The referee, T. Le Bertre, is thanked for comments and suggestions that improved the paper.

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