Allegro Memo No. 2: AGB stars as calibrators for HIFI and ALMA

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Abstract

We present observations of the CO 6-5 line toward 20 AGB stars with the CHAMP+ instrument at the APEX telescope. The intensities of 1.3–81 K have uncertainties of ≈15% and may be used as a calibration scale for HIFI and ALMA. Except IRC+10216, the sources may also be compact enough for ALMA phase calibration.

Contents

1 Motivation and source selection

The calibration of astronomical observations is necessary to compare measurements taken at different times, with different telescopes, or at different wavelengths. Calibrating single-dish submillimeter telescopes including Herschel/HIFI requires a set of astronomical sources with a known high line or continuum brightness which are spread over the sky (Ossenkopf 2003). In the case of interferometers such as ALMA, calibration has more aspects (Laing 2006), but the flux and phase calibration are the most challenging, especially at high frequencies (Van der Tak 2009). This report presents observations of 20 AGB stars in the CO J=6→5 line. The sources have been selected on high brightness in low-J CO lines from Kerschbaum & Olofsson (1999), Sahai & Liechti (1995), Young (1995), Olofsson et al (1993) and Ryde et al (1999).

2 Observations and results

The observations were done during several runs in November 2008, July 2009 and October 2009 at the APEX telescope (Güsten et al 2006). The CHAMP+ receiver is a 2-colour multibeam receiver centered at the 690 and 810 GHz windows (Güsten et al 2008).

Two main modes of observing were considered. In the initial observing runs, small maps were made in a hexagonal pattern of size 40”x40”. The Appendix presents some of those maps. As only the central pixel sees the source, this mapping mode is not very efficient. Therefore, in later observing runs, only peak-up observations were done. Once the telescope was pointed, a long integration was performed to reach a high S/N. In almost all cases, the telescope pointing was done on the source itself using a cross of 5 by 5 points. The telescope focus was normally done on a planet.

The receiver temperatures for the CHAMP+ array are typically ≈400 K SSB for the CO 6-5 tuning. All observations were typically done with precipitable water vapour (PWV) levels between 0.2 and 0.6 mm. This is equivalent to a system temperature between 1000-3000 K for the source elevations of 30 to 70 degrees. The integration times range from 1 minute for the brightest sources to 10 minutes for the weakest ones.

The backend configuration uses two FFTS modules with a bandwidth of 1.4 GHz, which are combined with a small overlap region yielding a total backend coverage of 2.4 GHz. The backend resolution is either 1024, 2048, 4096 or 8192 channels, equivalent to a ΔV of 0.08 $\mathrm{km\,s^{-1}}$, 0.16 $\mathrm{km\,s^{-1}}$, 0.32 $\mathrm{km\,s^{-1}}$or 0.64 $\mathrm{km\,s^{-1}}$.

The data were reduced with the CLASS software using standard procedures. Table 1 gives the results, while Table 2 gives the observing log. The last column of Table 1 gives the spectral resolution applicable to that observation. The observed intensities assume a sideband gain of 14 dB as measured in August 2009 by the instrument team.

3 Calibration and uncertainty

The calibration of the data was done using external Hot and Cold loads at physical temperatures of 285 K and 75 K. This hot/cold calibration was done typically every 5-10 minutes. The telescope staff and the instrument team have observed planets to allow estimating the beam efficiencies (Güsten et al 2008). Mars, Jupiter and Uranus were observed during the runs, but we use only Mars to estimate the efficiencies, since Jupiter is much more extended than our sources and Uranus is too weak. The measurements indicate a value of $\eta_{\rm mb}$=0.42 ± 0.02 where the error bar represents the variation in $\eta_{\rm mb}$ from run to run. See the CHAMP+ calibration weblog[1] for further details.

The different contributions to the calibration uncertainty are :

1. Beam efficiency: repeated observations during different runs indicate an uncertainty of 5% as discussed above.

2. Hot and cold loads: The intensity scale is proportional to (J_ν(hot) − J_ν(cold)), where $J_\nu(T)$ is the radiation field at the observing frequency ν, equal to $\eta_c B_\nu(T)$ where η_c is the coupling efficiency and $B_\nu(T)$ is the Planck function at the load temperature. The temperature sensors on the loads are accurate to better than 1 K, and the beam coupling to the loads has been measured during commissioning and is assumed to be stable. Possible systematic effects are temperature gradients between the sensors and the actual blackbody, and standing waves coming from reflection off the liquid nitrogen surface and the blackbody itself. Assuming that these are minor effects, we estimate an upper limit on this error source of 5%.

3. Sideband ratio: The image sideband is filtered out with a Martin-Pupplett interferometer. The achieved rejection is better than 10 dB across the IF band, and is likely to be >15–20 dB for the CO 6-5 line at the IF band center. A fraction $\eta_{\rm sb}$ of the line peak is measured, with $\eta_{\rm sb}$=0.95–0.99, leading to a 5% calibration uncertainty.

4. Pointing accuracy: The absolute pointing accuracy of the APEX telescope is 3–4″, but the pointing was corrected before each of our observations, it should be accurate to 1–2″. For point-like emission in a Gaussian telescope beam with FWHM = 10″, an 1″ offset reduces the intensity by 2.5% and a 2″ offset by 10%. Thus pointing again introduces a 5% uncertainty.

5. The atmospheric model: It is difficult to estimate the intrinsic accuracy of the model used at the telescope to estimate the atmospheric opacity from the sky brightness (Pardo et al 2001), so we give an empirical estimate. The line intensities in the two backend sections differ by 5–10%, due to the presence of a strong atmospheric absorption feature in one subband that was not fitted properly by the atmospheric model. Averaging the two subbands reduces this error to about ±5%.

We estimate the overall calibration uncertainty as the quadratic sum of these contributions, which is 11%, or 15% when allowing for systematic effects.

Some of the sources were observed at several opportunities, and typical variations are of the order of 5-10%. Larger variations are found when sources are observed during day-time. Those measurements are less reliable as rapid temperature changes affect the dish shape and specially the focus position, and even a small z-focus variation is noticeable. Therefore if a focus was not performed shortly before the observation, we consider the result unreliable. The repeated observations indeed show this effect, with lower fluxes in those cases.

[1] `http://www.mpifr.de/div/submmtech/heterodyne/champplus/champmain.html`

4 Source size and phase calibration

The suitability of our sources as phase calibrators for ALMA depends on the size of the emitting region. This size is unknown; an upper limit is given by the size of the J=2-1 emission which has been measured with the Submillimeter Array towards VY CMa, π^1 Gru and V Hya to be 5–10″ (Hirano et al 2004; Chiu et al 2006; Muller et al 2007). The one exception is IRC+10216 whose envelope extends over $\gtrsim$10″ (e.g., Schöier et al 2007). For this source, the Jupiter efficiency may actually be preferred over the Mars value; however, we prefer to present one consistent set of measurements in Table 1.

The size of the 6-5 emission may be estimated by comparing our measured intensities with those by Kemper et al (2003) who used the JCMT with an 8″ beam. In the case of VY CMa, Kemper et al measured $T_{\rm mb}$ = 4.4 K, and the intensity ratio with APEX of 1.63 is consistent with the value of 1.56 expected if the emission is unresolved with both telescopes (size $\lesssim$1″). This estimate is in agreement with the following more theoretical line of thought. In the model by Muller et al (2007) for the envelope of VY CMa, the temperature reaches 83 K (the location of the J=6 level of CO) at a radius of 3×10^{16} cm, which corresponds to 1″.33 at a distance of 1.5 kpc.

We consider the size of the VY CMa envelope as an upper limit for the other stars, since VY CMa has one of the highest known mass loss rates among AGB stars (e.g., Polehampton et al 2009). However, for WX Psc, Kemper et al measured an intensity of 2.3 K, which is below the APEX value. Maybe this source is variable, or the emission is spatially resolved with the JCMT. This source should be re-observed. Unfortunately, VY CMa and WX Psc are the only sources which have been observed with JCMT and APEX.

5 Conclusions and future work

With main beam temperatures of $\gtrsim$1 K, our sources are detectable in a minute, which is bright enough to serve as flux calibrators for HIFI Band 2 and ALMA Band 9. With the exception of IRC+10216, the sources may be compact enough for ALMA phase calibration, and we recommend that the ALMA Calibrator Survey includes these objects to find out.

In the future, we plan to augment this list with more stars to improve the sky coverage. We also plan more monitoring of selected stars to assess whether variability is significant, which would be a problem for flux calibration. The CO emission originates far out in the stellar wind, and variability on timescales of days or weeks are unlikely, while variations on timescales of months or years are quite possible. Finally we plan to present observations of the CO J=7-6 line of the same stars, which may be used to calibrate HIFI Band 3 and ALMA Band 10.

Acknowledgements

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Sahai & Liechti 1995: A&A 293, 198
Schöier et al 2007: ApJ 670, 766
Young 1995: ApJ 445, 872

Table 1: ^{12}CO ($J = 6-5$) observations of a selected list of AGB stars. The line position and FWHM are also presented. The T_{MB} (K) assumes a beam efficiency of 0.42, and the error bars presented are the 1σ rms values.

Source	T_{MB} (K)	$V_{\rm LSR}$ km s^{-1}	FWHM km s^{-1}	Δv km s^{-1}
IRC+10216	81.0 ± 1.75	−25.6	18.7	0.16
O Cet	34.5 ± 0.75	+46.8	4.8	0.16
R Dor	17.1 ± 0.33	+7.3	9.1	0.64
Ep Aqr	9.3 ± 0.53	−33.7	1.9	0.16
L2 Pup	7.7 ± 0.27	+33.4	3.44	0.64
RAFGL 3068	7.6 ± 0.56	−30.8	16.6	0.16
R Hor	7.1 ± 0.50	+37.3	6.04	0.64
IRAS15194-5115	6.92.03	−15.5	29.1	0.64
IK Tau	6.6 ± 0.76	+34.7	24.2	0.64
R And	6.3 ± 0.91	−15.2	10.5	0.16
V Hya	6.3 ± 1.09	−17.0	24.9	0.32
07454-7112	6.2 ± 0.82	−38.9	15.3	0.16
W Aql	6.1 ± 1.12	−23.1	36.7	0.64
π^1 Gru	5.7 ± 0.70	−11.2	16.7	0.64
TX Psc	4.4 ± 1.00	+12.7	2.1	0.64
VY CMa	2.8 ± 0.76	+26.5	53.9	0.64
WX Psc	2.4 ± 0.35	+9.6	24.2	0.32
R Scl	1.5 ± 0.33	−19.4	23.0	0.32
R For	1.3 ± 0.20	−3.1	22.7	0.32
V1943 Sgr	1.3 ± 0.08	−15.2	7.3	0.64

Table 2: Source list and observing dates with corresponding APEX scan numbers

Source	α_{2000}	δ_{2000}	Date	Scans
IRC+10216	$09^h47^m57.3^s$	$+13°16'42.9''$	11 Nov 2008	61419
O Cet	$02^h19^m20.8^s$	$-02°58'40.9''$	21 Oct 2009	73248
R Dor	$04^h36^m45.6^s$	$-62°04'37.8''$	10 Nov 2008	60930 – 60932
Ep Aqr	$21^h46^m31.9^s$	$-02°12'45.8''$	23 Oct 2009	73576 – 73577
L2 Pup	$07^h13^m32.3^s$	$-44°38'23.1''$	11 Nov 2008	61346
RAFGL 3068	$23^h19^m12.4^s$	$+17°11'35.4''$	23 Oct 2009	73582 – 73584
R Hor	$02^h53^m52.8^s$	$-49°53'22.7''$	10 Nov 2008	60949 – 60951
IRAS 15194-5115	$15^h23^m04.9^s$	$-51°25'59.0''$	17 Jun 2009	33215
IK Tau	$03^h53^m28.8^s$	$+11°24'22.6''$	22 Oct 2009	73253
R And	$00^h24^m01.9^s$	$+38°34'37.1''$	24 Oct 2009	73965 – 73970
V Hya	$10^h51^m37.2^s$	$-21°15'00.3''$	11 Nov 2008	61365
07454-7112	$07^h45^m02.8^s$	$-71°19'42.2''$	11 Nov 2008	61378 – 61408
W Aql	$19^h15^m23.4^s$	$-07°02'49.9''$	21 Oct 2009	73141 – 73147
π^1 Gru	$22^h22^m44.2^s$	$-45°56'52.6''$	17 Jun 2009	33353 – 33357
VY CMa	$07^h22^m58.3^s$	$-25°46'03.2''$	17 Jun 2009	33432
TX Psc	$23^h46^m23.5^s$	$+03°29'12.4''$	24 Oct 2009	73716 – 73917
WX Psc	$01^h06^m26.0^s$	$+12°35'53.0''$	24 Oct 2009	73924 – 73959
R Scl	$01^h26^m58.1^s$	$-32°32'35.5''$	23 Oct 2009	73591 – 73593
R For	$02^h29^m15.3^s$	$-26°05'55.7''$	24 Oct 2009	73978 – 73984
V1943 Sgr	$20^h06^m55.2^s$	$-27°13'29.8''$	14 Sep 2008	46122 – 46140

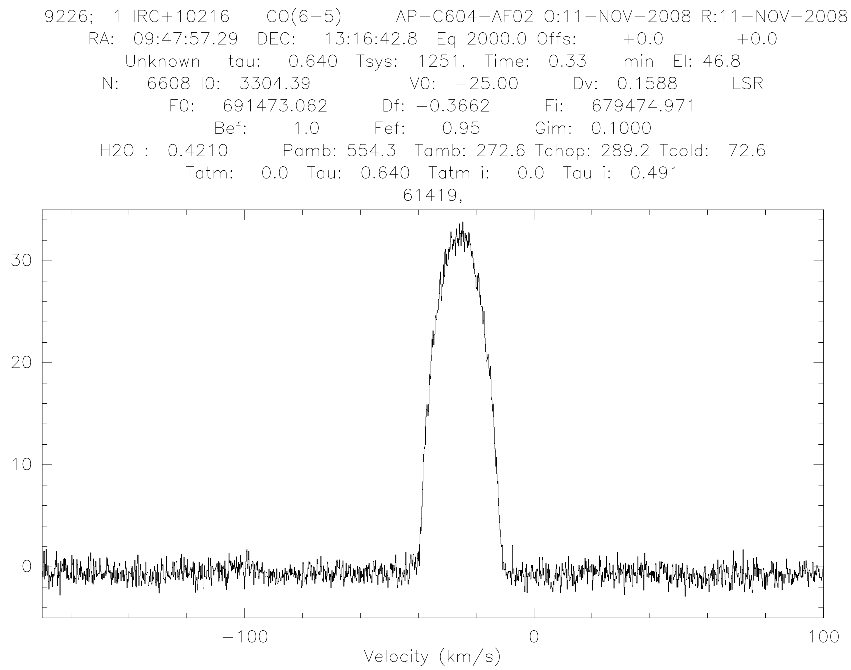

Figure 1: IRC+10216 CO(6-5) spectrum

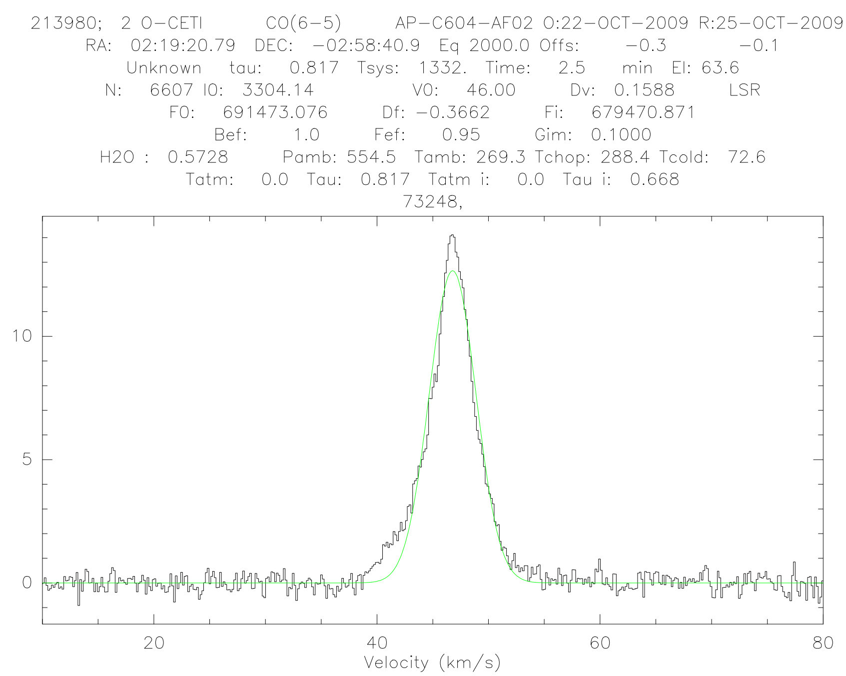

Figure 2: O-Ceti CO(6-5) spectrum

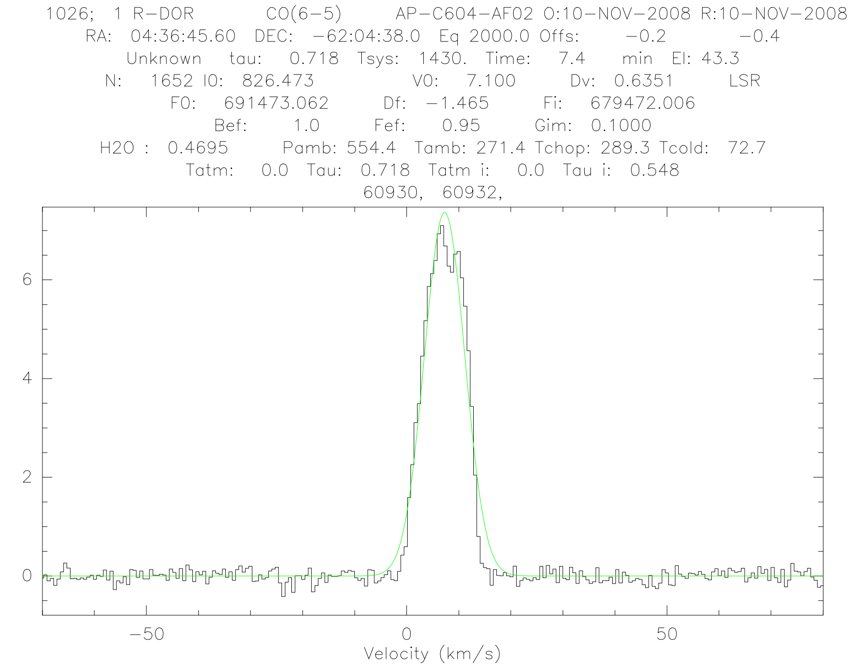

Figure 3: R-DOR CO(6-5) spectrum

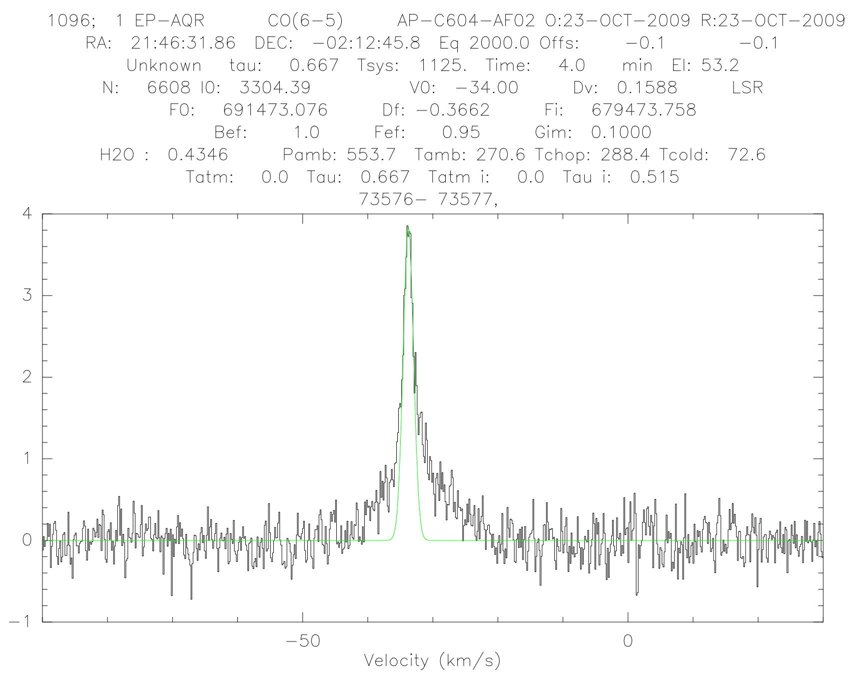

Figure 4: EP-AQR CO(6-5) spectrum

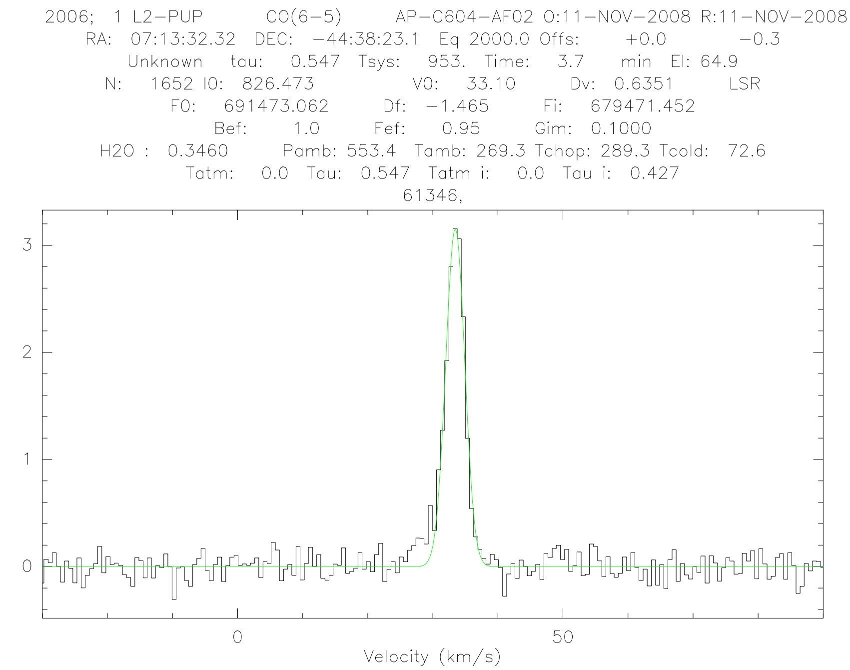

Figure 5: L02-pup CO(6-5) spectrum

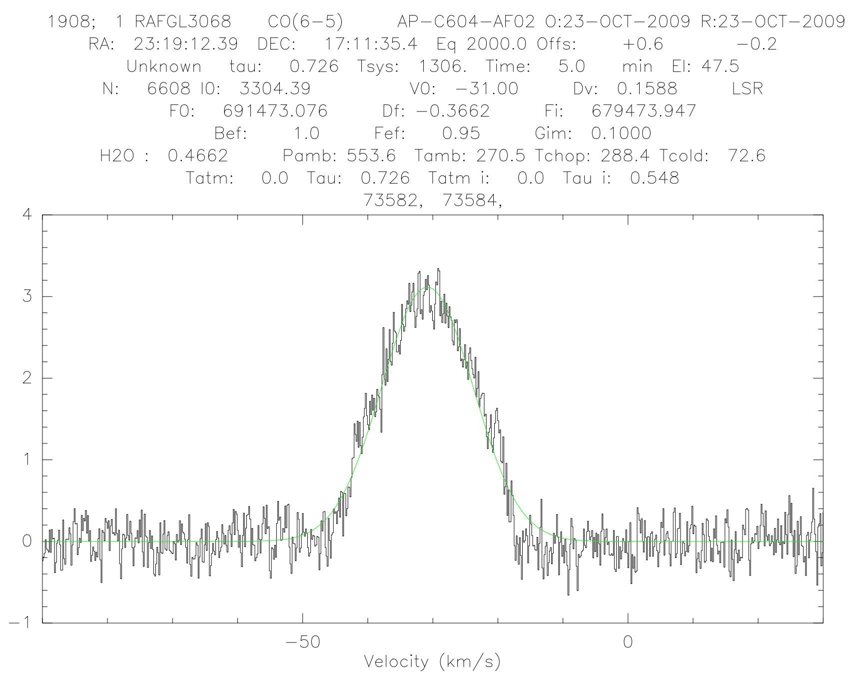

Figure 6: RAFGL-3068 CO(6-5) spectrum

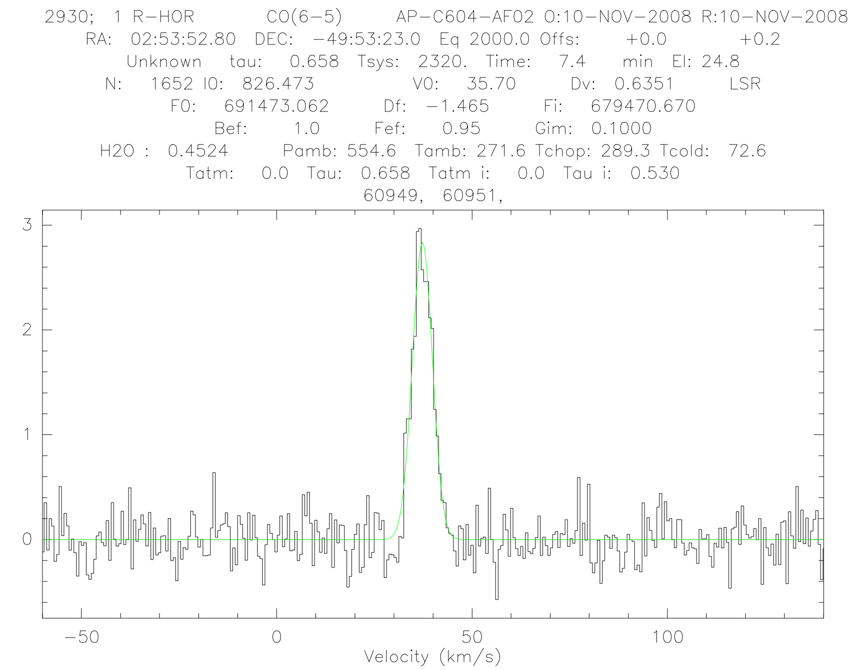

Figure 7: R-HOR CO(6-5) spectrum

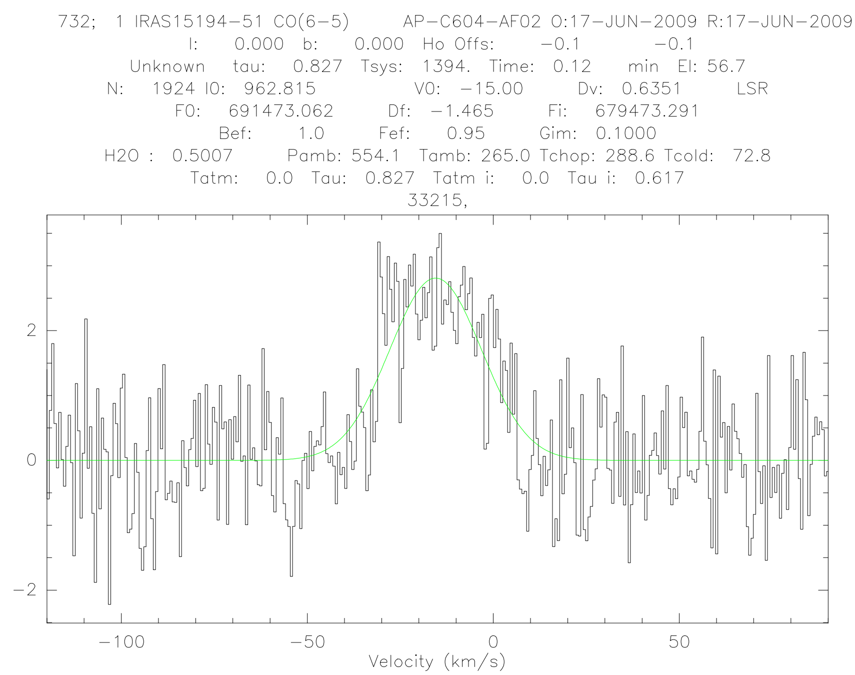

Figure 8: IRAS-15194 CO(6-5) spectrum

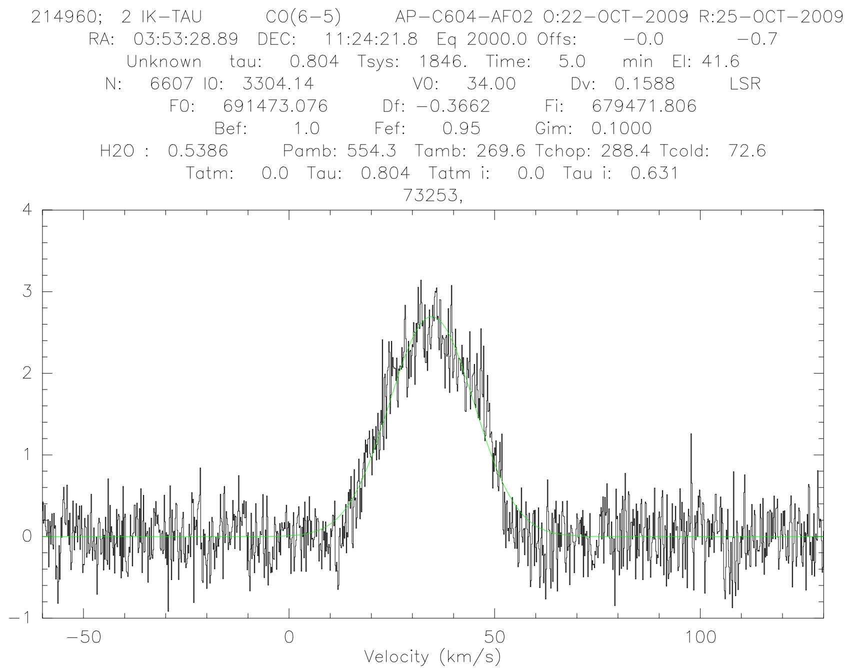

Figure 9: IK-TAU co(6-5) spectrum

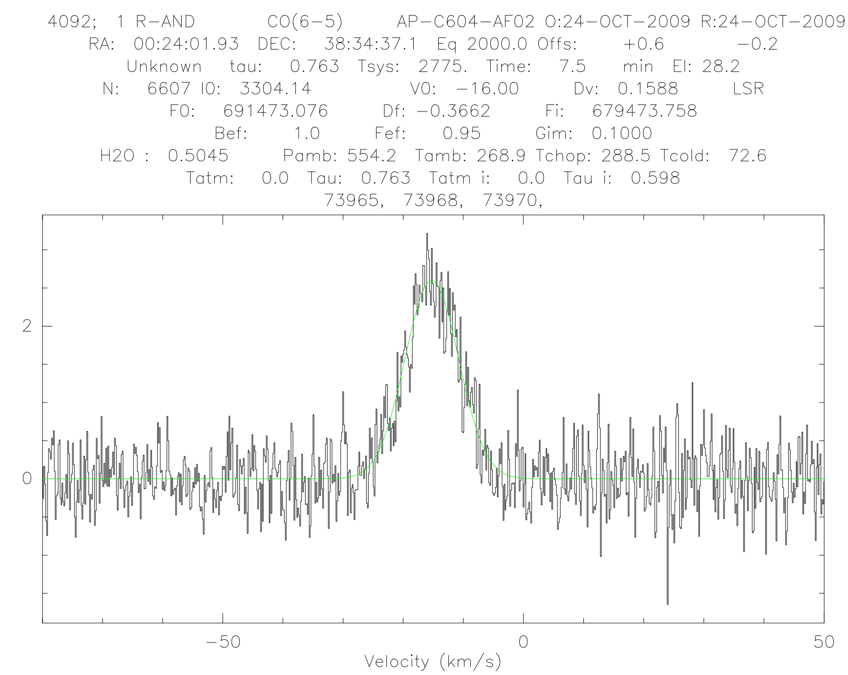

Figure 10: R-And CO(6-5) spectrum

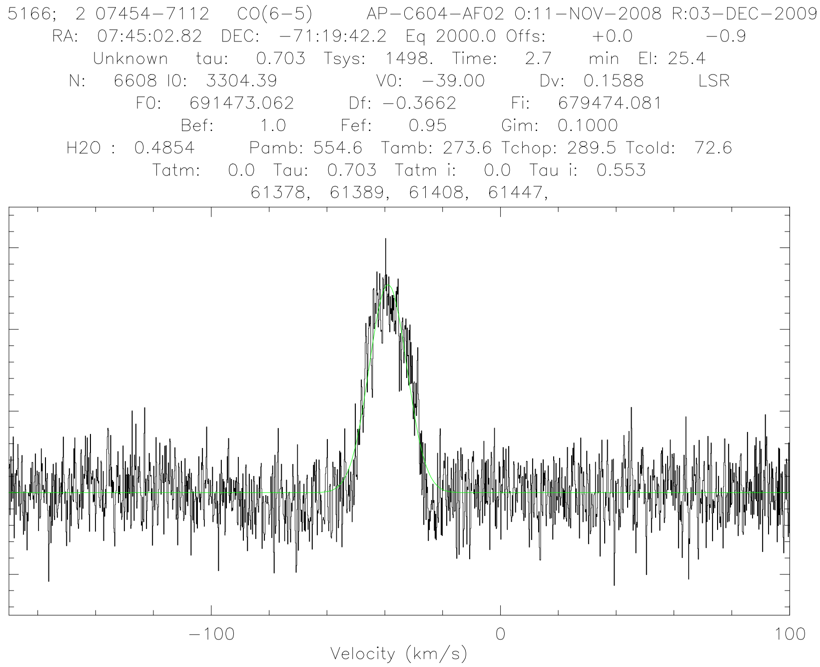

Figure 11: 07454-7211 CO(6-5) spectrum

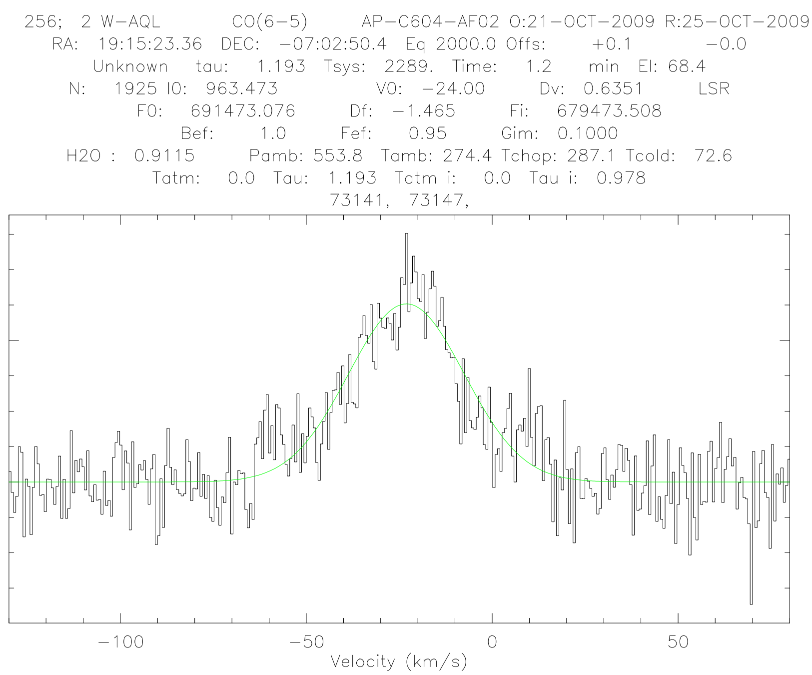

Figure 12: W-Aql CO(6-5) spectrum

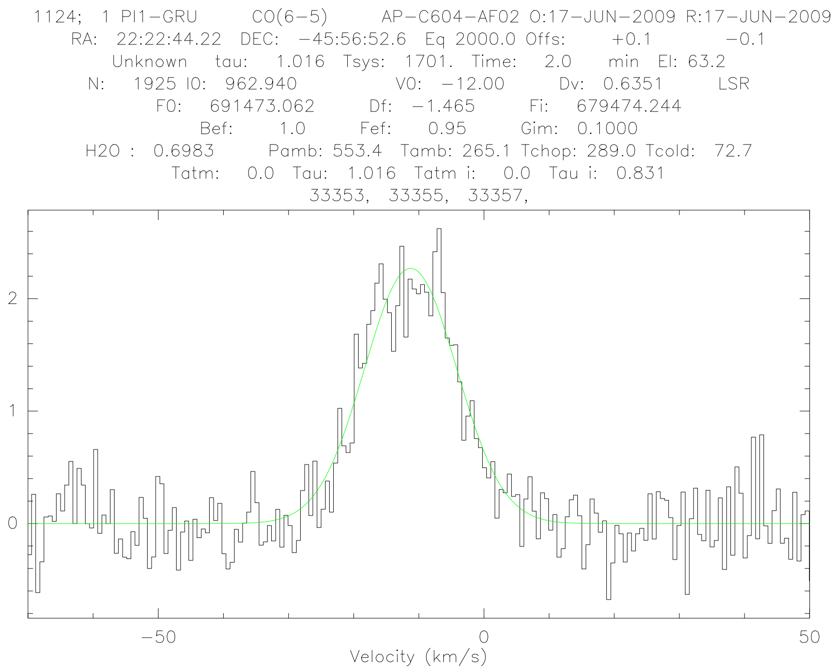

Figure 13: PI1-Gru CO(6-5) spectrum

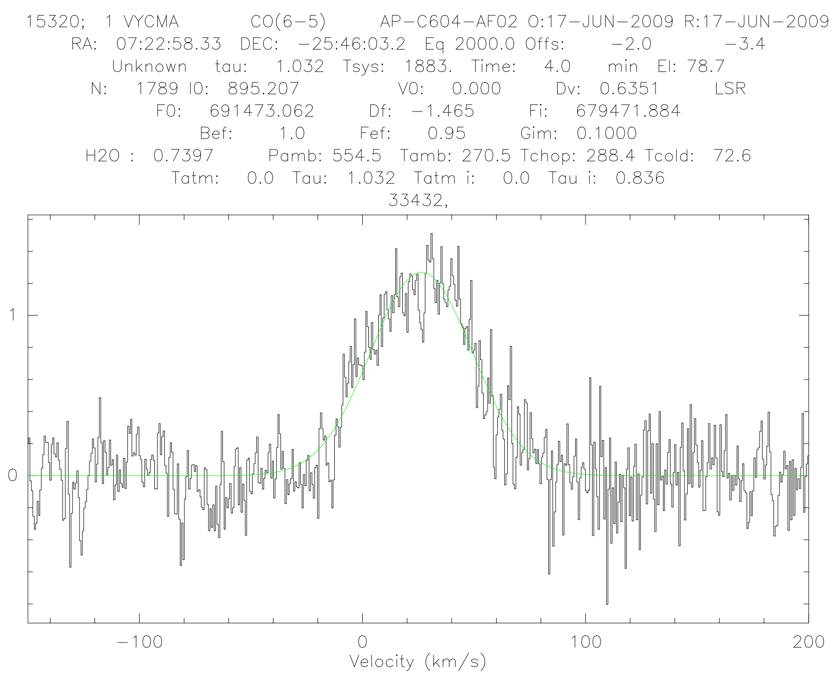

Figure 14: VYCMA CO(6-5) spectrum, probably not properly focused.

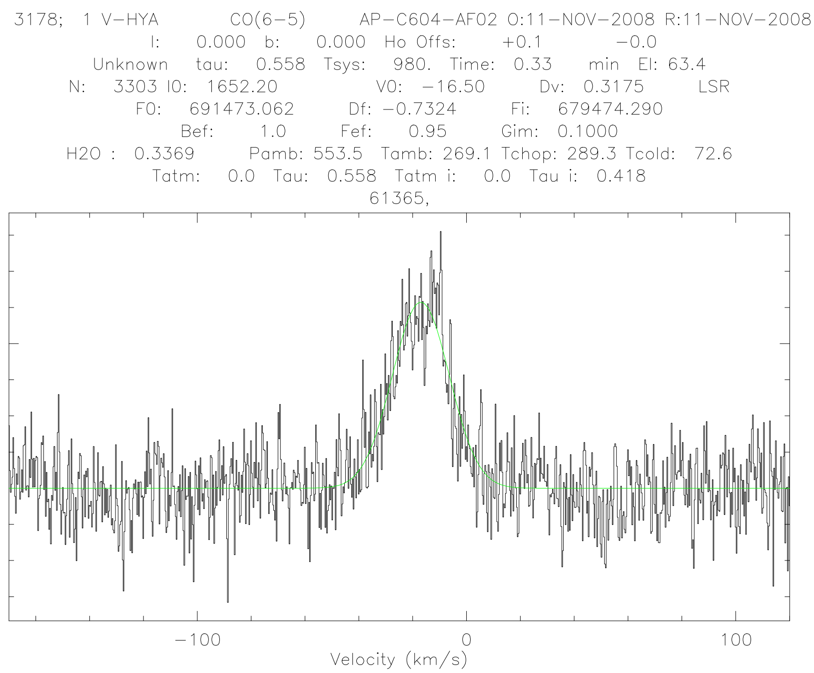

Figure 15: V-Hya co(6-5) spectrum. Pointing offset of 3” from central position.

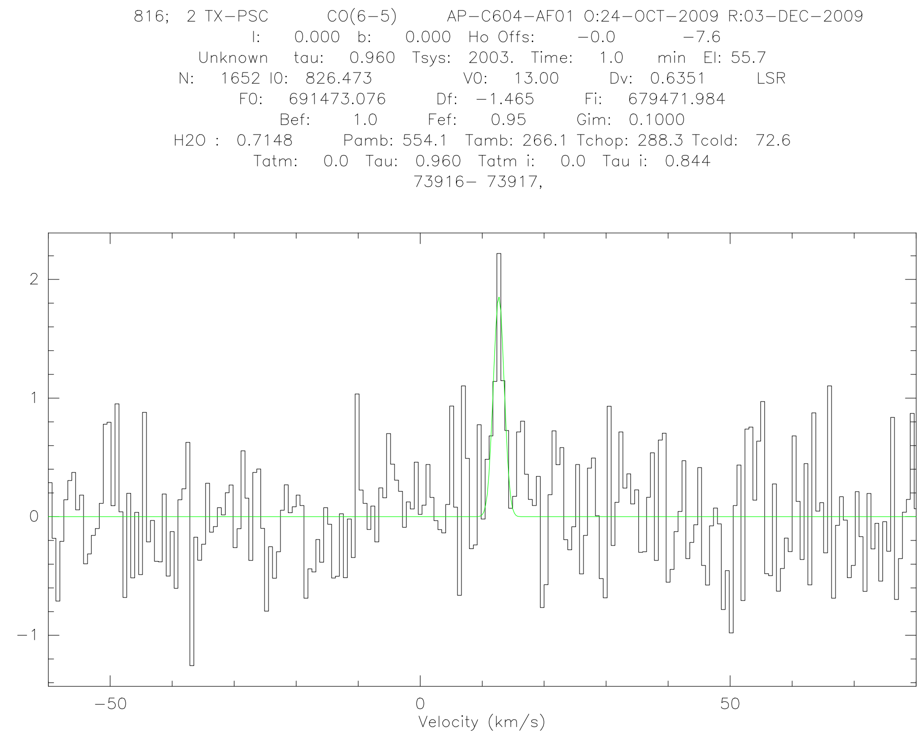

Figure 16: TX-Psc co(6-5) spectrum. Not properly pointed.

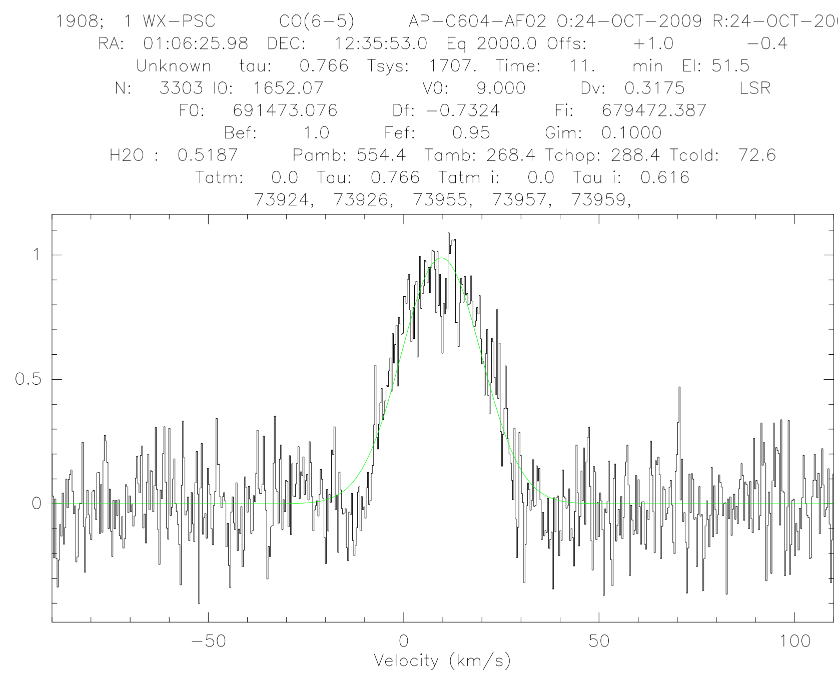

Figure 17: WX-Psc co(6-5) spectrum

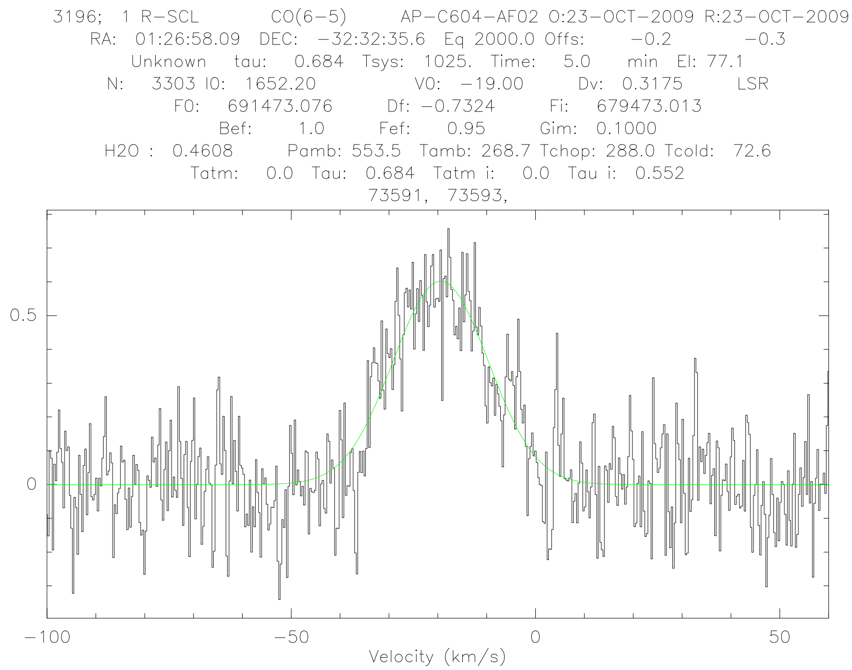

Figure 18: R-Scl co(6-5) spectrum

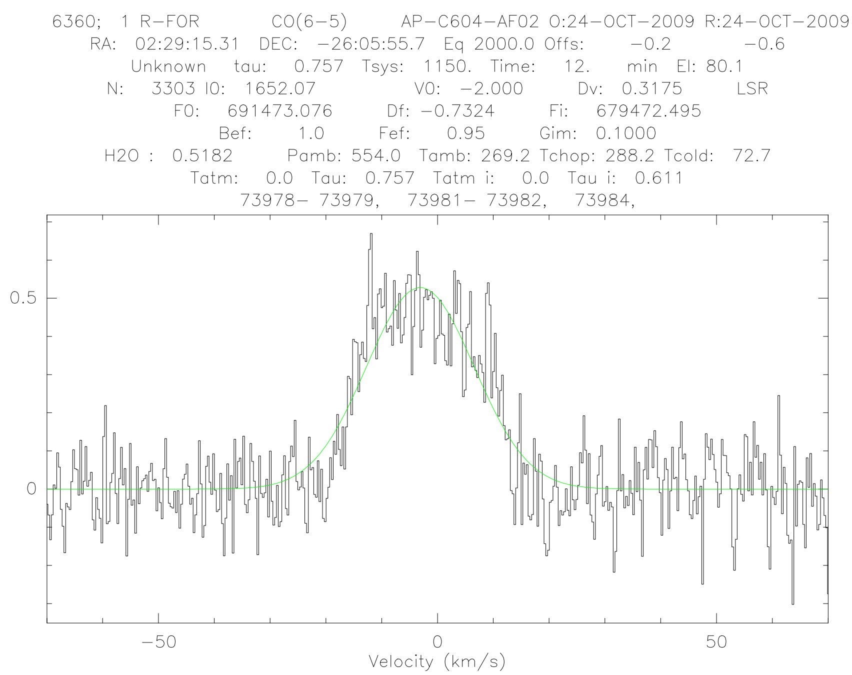

Figure 19: R-For co(6-5) spectrum

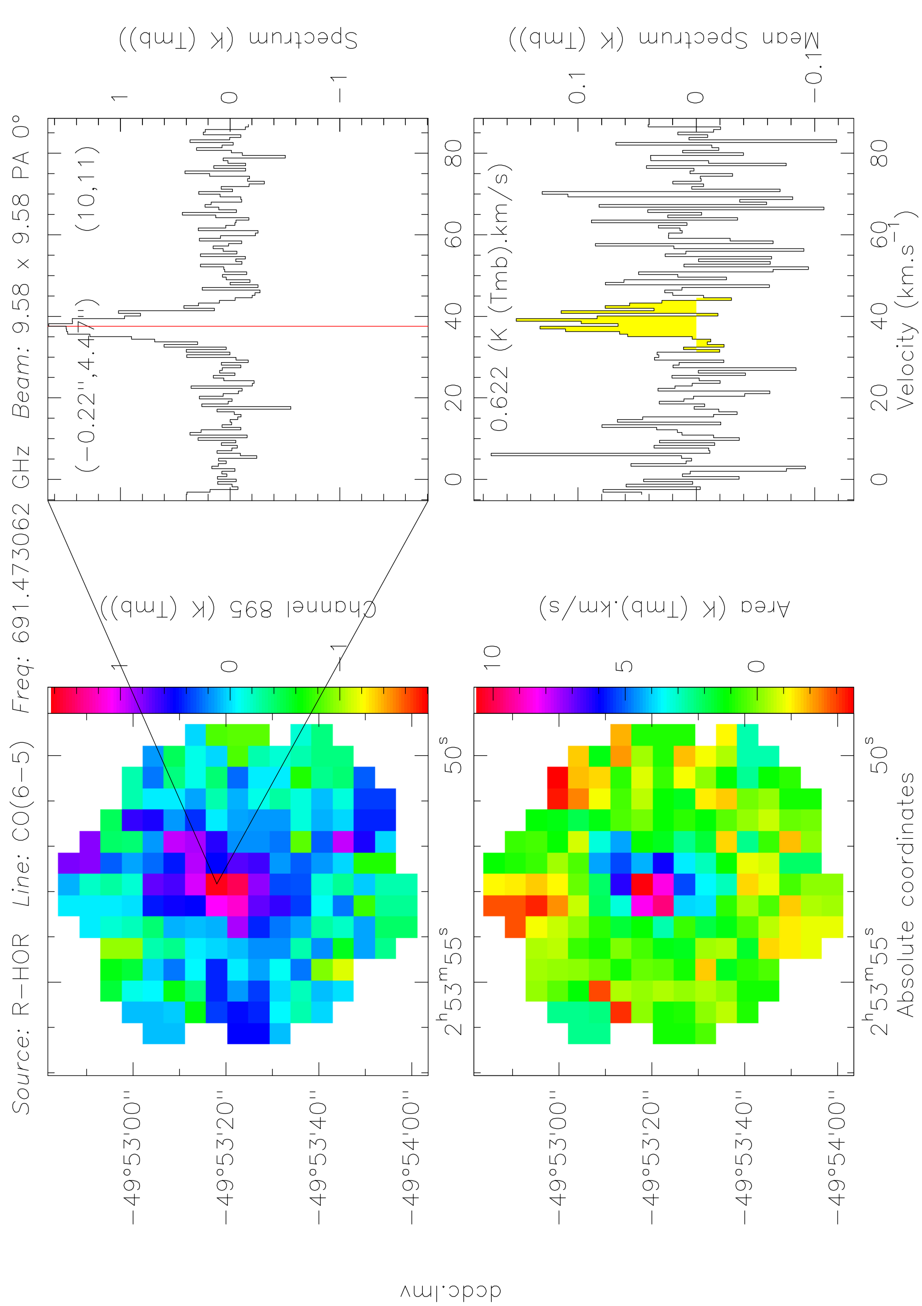

Figure 20: R-HOR co(6-5) map

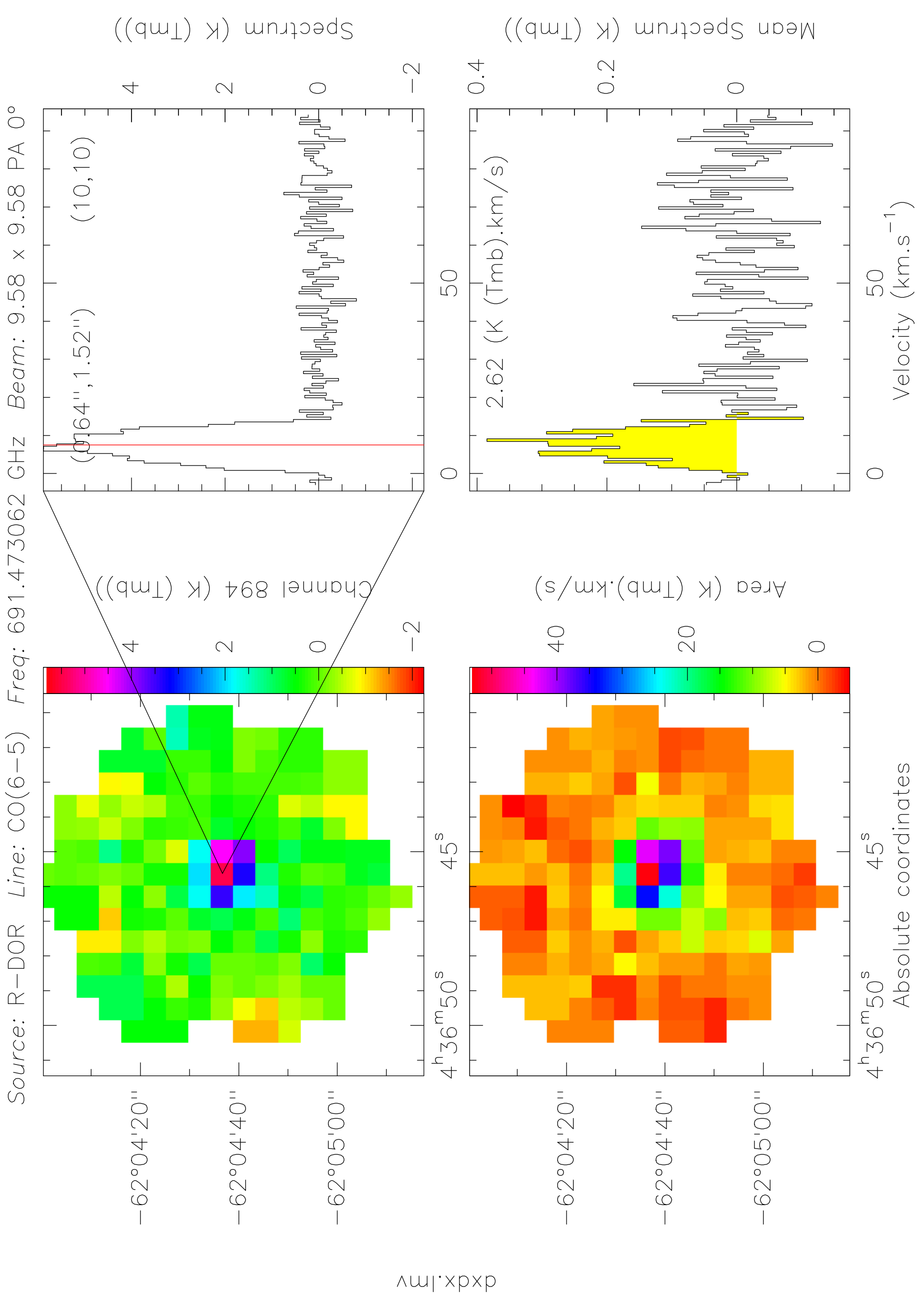

Figure 21: R-DOR co(6-5) map

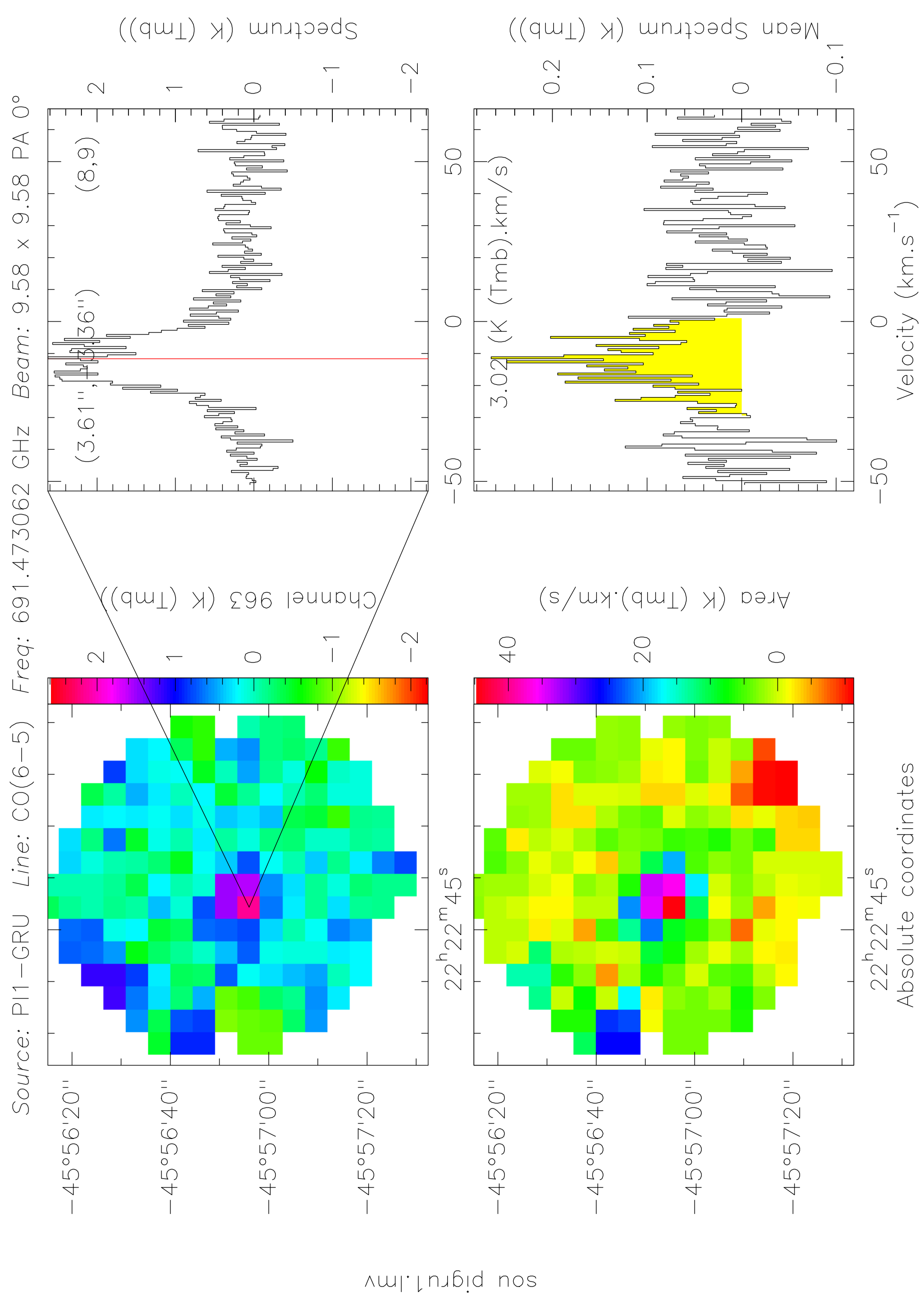

Figure 22: PI1-GRU mapping in CO(6-5)

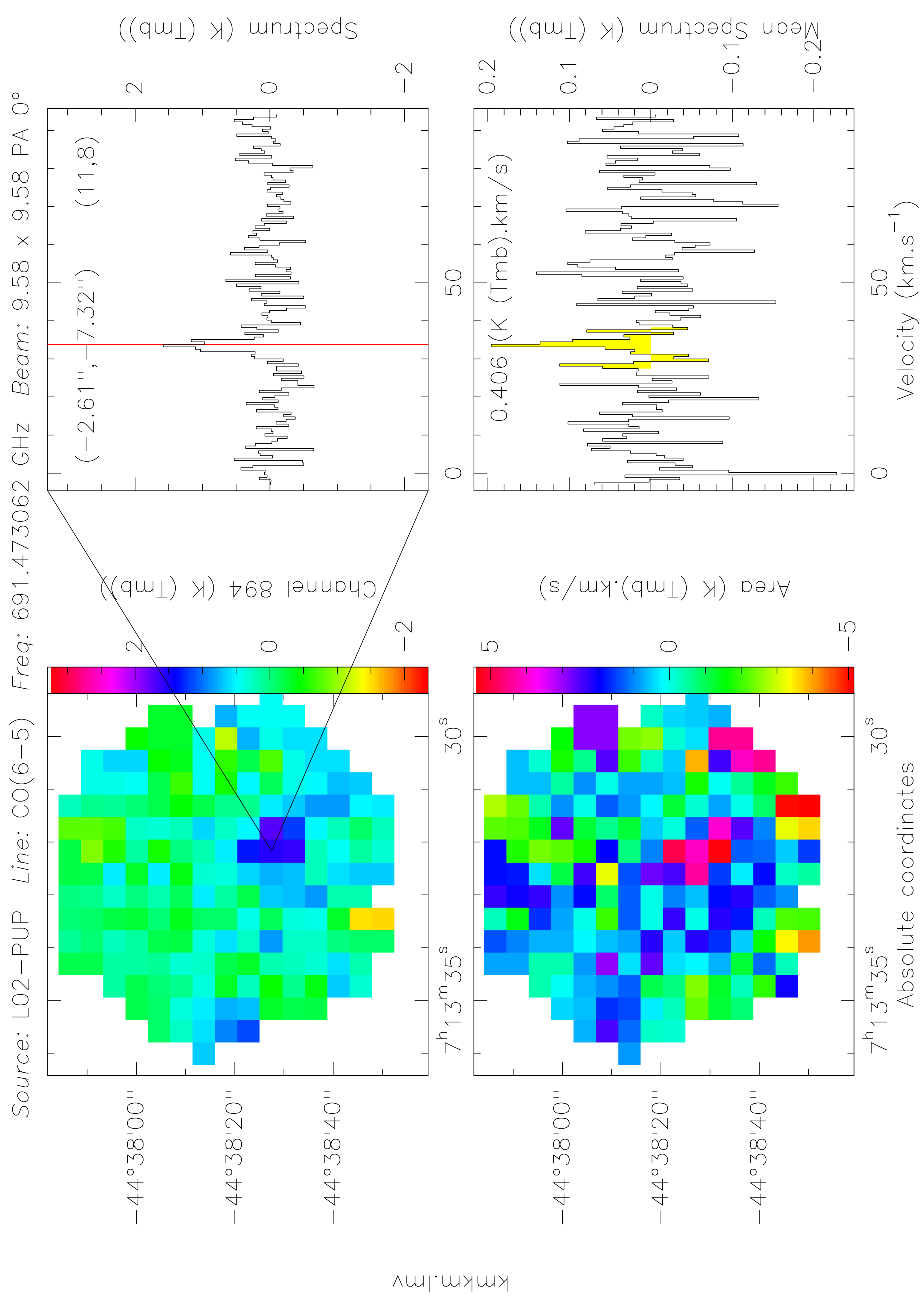

Figure 23: L02-pup mapping in co(6-5)

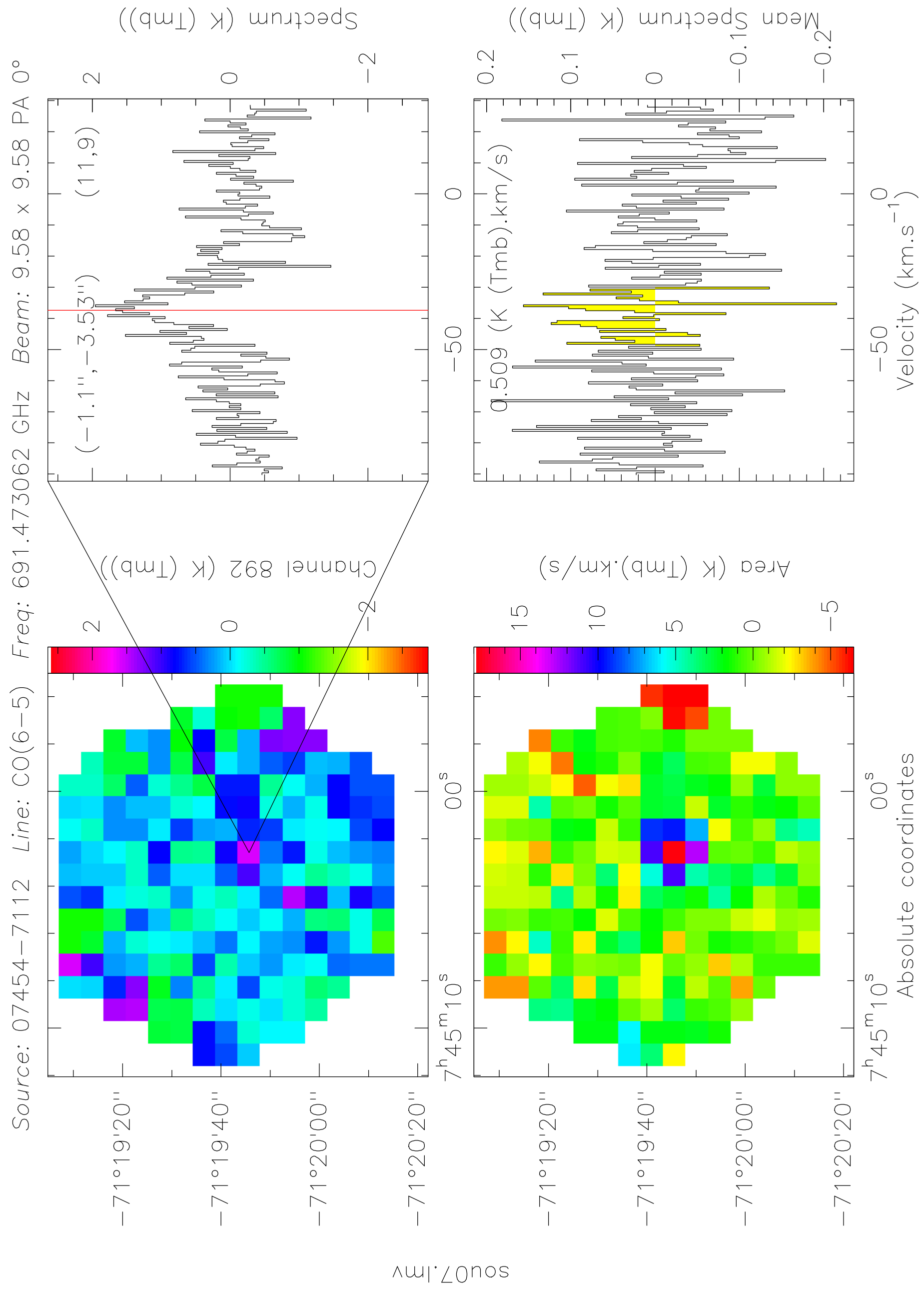

Figure 24: 07454 mapping in co(6-5)

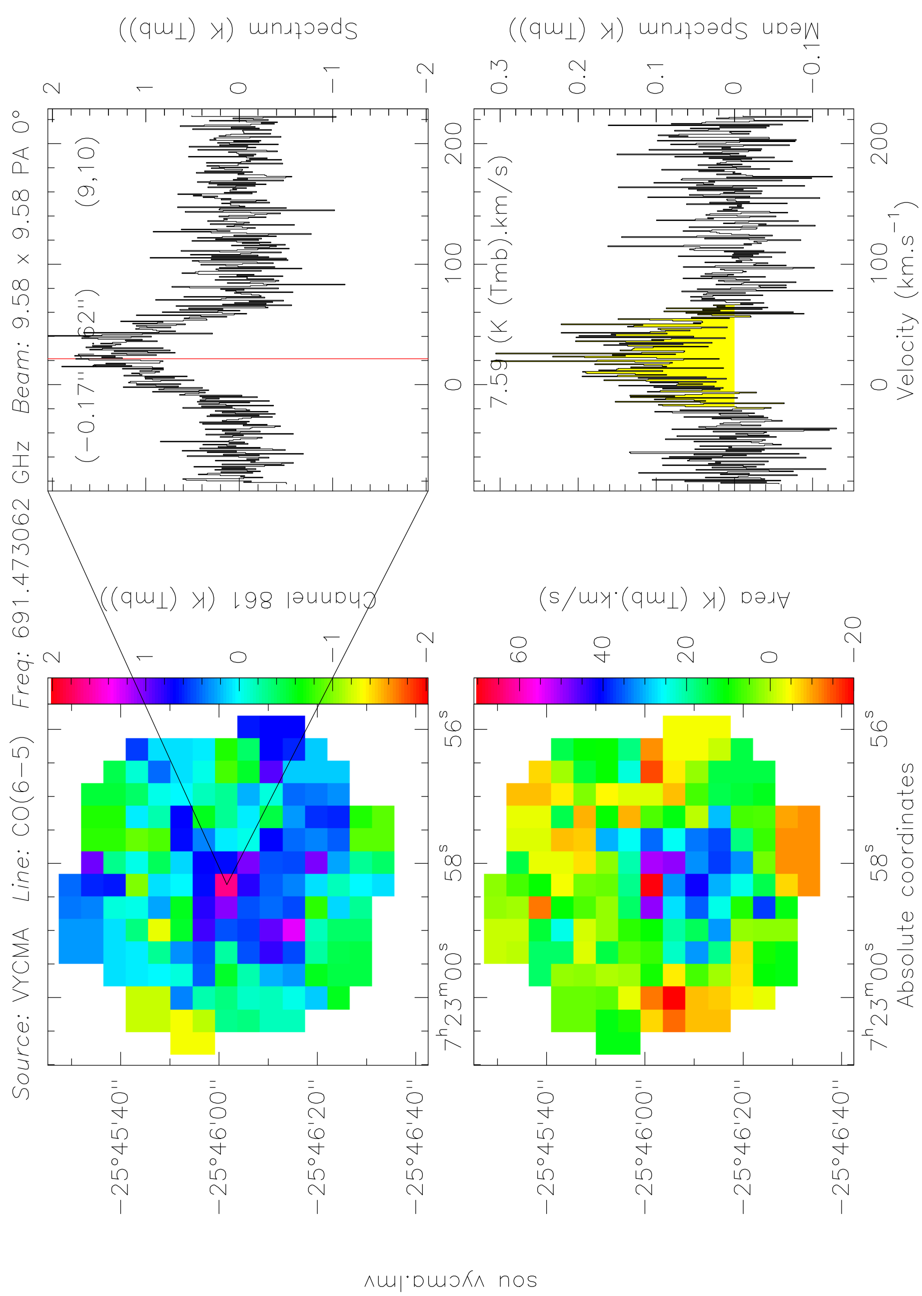

Figure 25: VY-CMA map, extended structure? focus problem during day-time?