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Mass Calibration and Hydrodynamics in the Cepheus Flare

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Using the 'Mini' radiotelescope of Harvard and POM-2 in France, we have observed a cloud of the nearby Cepheus complex in ^{12}CO and ^{13}CO, J:1→0 and 2→1, at a resolution of 0.7 pc. A uniform (2-1)/(1-0) line ratio has been found over the cloud for both isotopes, implying low excitation temperatures of $\lesssim$10 K and small opacities ($0.1<\tau<2$). The isotopic ^{13}CO/^{12}CO line ratios fluctuate by a factor of 5 from point to point. The H_2 column-densities derived from extinction measurements, γ-ray observations and LTE or LVG models (applied to ^{13}CO data) agree within a factor of 2.

The velocity field in the cloud is quite singular and highly organized on a 10-pc scale. The observed field is quite consistent with the 'slow flow' of a perfect fluid around a spherical obstacle: 5000 $M_\odot$ thus move at ~3 km s^{-1}, implying a kinetic energy of 5 10^{47} erg.

INTRODUCTION

Mapped in CO at a resolution of 0.5° by Lebrun (1986) and Grenier *et al.* (1989), the Cepheus Flare region contains a nearby molecular complex at ~300 pc. It is comparable in size to the Orion or Taurus clouds though it sheds little star formation.

The eastern cloud of the complex exhibits unusually wide CO lines. At the same position, a radio spur can be seen at 408 and 1420 MHz. The non-thermal origin of the radiation, most likely due to synchrotron emission by high-energy electrons, strongly suggests the presence of a shock crossing the cloud.

To constrain the cloud characteristics, a multi-transition study has been undertaken. We fully surveyed the cloud ($111°<l<117°$, $14°<b<19°$) with the 'Mini' in the ^{12}CO(J:1→0) line, at a resolution of 8'.7 FWHM, i.e. 0.7 pc locally. A set of 80 positions has been selected as representative of the entire cloud and observed in ^{13}CO(J:1→0) with the 'Mini', then in ^{12}CO(J:2→1) and ^{13}CO(J:2→1) using the POM-2 millimeter telescope. All the data have been scaled to the same resolution.

One goal is to compare the H_2 mass estimates obtained in this cloud by various means such as γ-ray observations, extinction measurements or modelling the CO line radiative transfer. Free from appreciable absorption, γ rays can trace H_2 column-densities assuming a uniform penetration of the cosmic rays in the atomic and molecular gas media. EGRET γ-ray observations of the Cepheus Flare region yield a CO-to-H_2 conversion factor $X=(0.92 \pm 0.14)\ 10^{20}$ mol cm^{-2} K^{-1} km^{-1} s (Digel *et al.* 1995a), equal to that measured in Orion and

Ophiuchus. The higher values obtained when using the former COS-B data were likely due to the presence of bright, unresolved γ-ray sources in the field of view (Digel *et al.* 1995b). The new X ratio is used here.

Another goal is to understand the puzzling velocity structure of the eastern cloud. A purely kinematical scenario is proposed hereafter as a first approximation.

Mass calibration

The new observations at higher resolution show that the unusually wide CO lines in the eastern cloud are composed of up to 3 lines that have been fitted by gaussians. To study line ratios, the more accurate integrated line intensity $W_{CO} = \int T.dv$ has been prefered over peak temperature. Figure 1a illustrates the good correlation between J:2→1 and J:1→0 intensities (here in ^{12}CO). The error bars include line-fitting errors and a 10% uncertainty in the absolute calibration of the spectra. For both isotopes, the data are consistent with a uniform (2→1)/(1→0) intensity ratio over the whole cloud. Linear fits to the data, using a maximum-likelihood technique and information matrix (Strong 1985), yield (2→1)/(1→0) W_{CO} ratios of **0.89 ± 0.03** and **0.63 ± 0.03** for the ^{12}CO and ^{13}CO isotopes, respectively. The ^{12}CO result nicely agrees with the average value of 0.9 measured at the solar circle (Sanders 1993). It is higher, however, than the ratios found in Orion A and B: 0.77 and 0.66 (Sakamoto *et al.* 1994).

Using simple LTE assumptions and treating both isotopes separately, the constant (2→1)/(1→0) ratios imply rather optically thin conditions for both ^{12}CO and ^{13}CO lines in the cloud and low excitation temperatures:

^{13}CO: $T_{ex} = 5.2 \pm 0.1$ K $\quad 0.1 < \tau_{1\to0} < 1 \quad \tau_{2\to1} \sim \tau_{1\to0}$

^{12}CO: $7 < T_{ex} < 10$ K $\quad 0.8 < \tau_{1\to0} < 2 \quad \tau_{2\to1} \sim 1.5\ \tau_{1\to0}$

Applying a more precise LVG model to the CO data gives opacities in the same range.

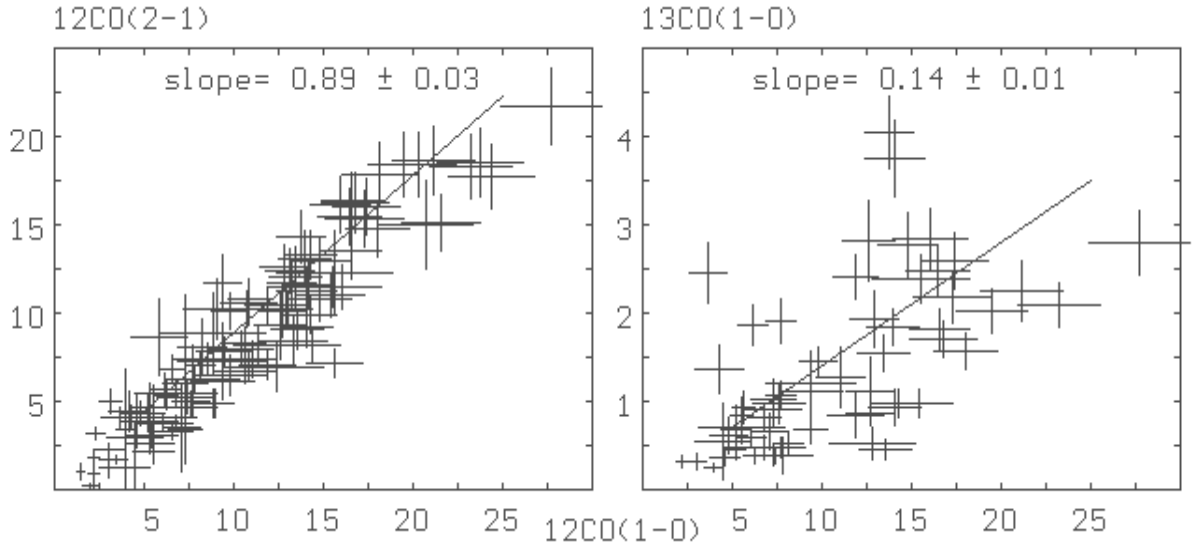


Fig. 1 W_{CO} in K km s^{-1}: **a)** ^{12}CO(2-1) versus ^{12}CO(1-0) **b)** ^{13}CO(1-0) versus ^{12}CO(1-0)

Figure 1b shows that the $^{13}CO/^{12}CO$ intensity ratios largely fluctuate from point to point. The variations do not depend on line strength, opacity, or position with respect to the core or edges of the cloud. The cold temperature may play an important role since, below 35 K, the formation of ^{13}CO molecules by isotopic fractionation is reinforced:
$^{13}C^+ + {}^{12}CO \rightarrow {}^{13}CO + {}^{12}C^+$.

Because of the optical thinness of the cloud, the kinetic temperatures and $N(H_2)$ column-densities derived from LTE and LVG models are fully consistent. Both models rely on a $N(H_2)/N(^{13}CO)$ ratio of $(5 \pm 2.5)\ 10^5$ (Dickman 1978). Figure 2 shows that these $N(H_2)$ estimates agree within a factor of 2 with those derived from measured W_{CO} intensities and the EGRET value of X. It should be noted that the fitted slope would get closer to 1, if the large uncertainty on the $N(H_2)/N(^{13}CO)$ ratio were reduced. Observational evidence indicates that faint γ-ray sources are not significantly contaminating the X value. Too many sources distributed like the CO on a few-parsec scale would be required. Extinction measurements and the gas-to-dust ratio of Bohlin et al. (1978) also give consistent, though less accurate, $N(H_2)$ estimates.

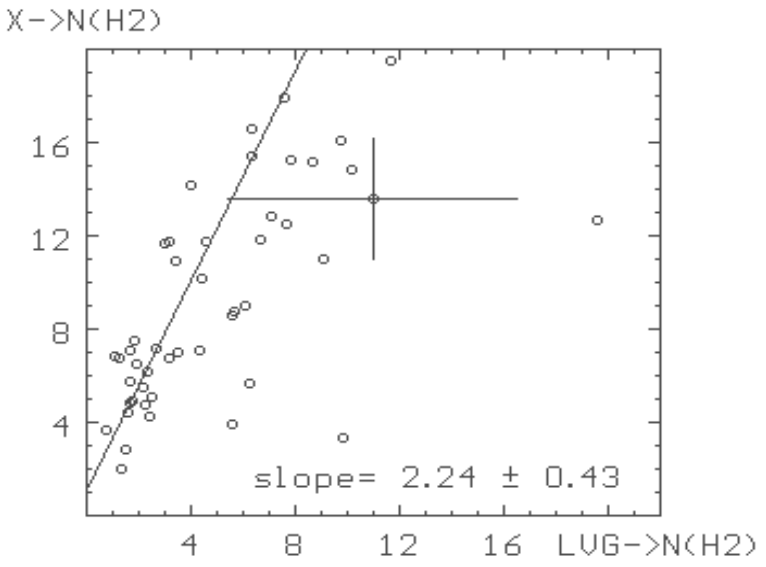
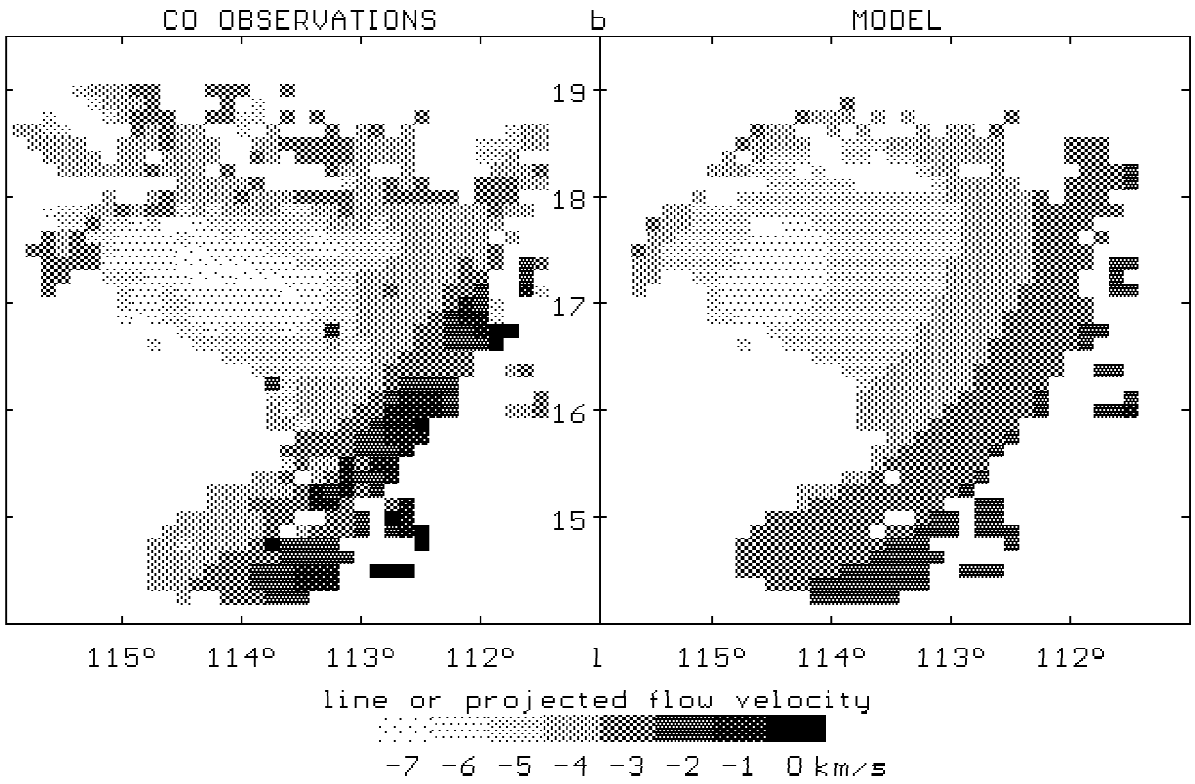


Fig. 2 Comparison of H_2 column-densities (in 10^{20} mol K^{-1} km^{-1} s) deduced from $^{12}CO(1\text{-}0)$ via X and from ^{13}CO via a LVG model.

Velocity field

Far from being randomly distributed, the velocity field in the eastern cloud appears to be highly organized on a 10-pc scale. For lines brighter than 1 K, the line central velocity is displayed in figure 3a as a function of the l and b coordinates. Concentric rings are clearly seen in the north-east region and stripes in the south-west, where lines are brighter. Displayed in a 3-D (l, b, v) plot, the points of the striped region are actually tightly confined to a plane sheet. The rings correspond to an expansion/infall of the gas while the stripes and plane to solid rotation around an axis parallel to the stripes. As a first approximation, the slow, quasi-laminar flow of a perfect fluid around a spherical obstacle can reproduce both structures together (Remy & Grenier 1996). The amplitude and direction of the impact velocity and the size of the obstacle (close to the cloud size of 20 pc) have been fitted to the 3-D data. The resulting velocities projected along the lines of sight are shown in figure 3b. In this purely kinematical scenario, CO emission from the flow corresponds to a mass of ~5000 $M_\odot$ moving at typically 3 km s^{-1}. The required kinetic energy amounts to 5 10^{47} erg. Hydrodynamical simulations of the distorsion of a dense cloud overtaken by a slow shock wave are underway to compare more realistic velocity fields to these distinctive features.



Observations: Velocity field in the cloud for lines brighter than 1 K.
Model: Velocity field projected along the lines of sight of a flow around a 'spherical body'.

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