Cm-wave continuum radiation from ρ Oph

The radio/H_2 correlation

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Outline

What is the spin up mechanism?

Bright radio continuum from ρ Oph W

H_2 – 31 GHz.

An interesting datum: 31 GHz – rovib H_2 correlation.

Conclusions

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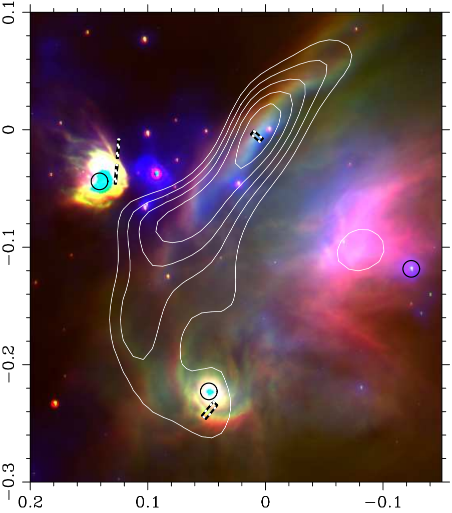
Insights from Ophiucus.



- MIPS 24 μm, IRAC 8μm, 2MASS 2.2μm, CBI2 contours.
- S 1 coincides with the brightest IR nebula, also brightest in PAHs.
- Yet no detectable radio continuum in S 1!

It’s not VSG depletion. It’s emissivity boost in ρ Oph W.

- If spinning dust emissivity per nucleon was independent of environment, then since PAH intensities are $\propto G_\circ$ (the local UV field)

  $\Rightarrow R = G_\circ \times I_\nu(31\mathrm{GHz})/I(\mathrm{PAH}\,11.3\,\mu\mathrm{m})$ should be constant.

- Given *Spitzer* IRS PAH spectroscopy, $G_\circ$ from *ISO*, and CBI2 mosaic, R is 42 times greater in Oph W than in S 1 (at 3 σ)

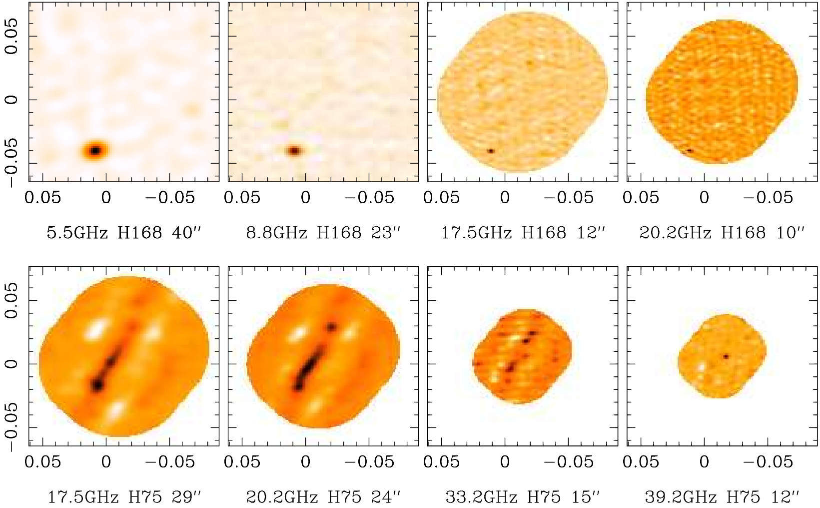
  → the zero-order approximation I(31) GHz $\propto N$(VSG) breaks down. Environmental factors boost the spinning dust emissivities in ρ Oph W.

What is boosting spinning dust in ρ Oph W?

- Not $G_\circ$: from *ISO* big-grain T_d in S 1 is $\sim$35 K and $>$ than in ρ Oph W.
- Plasma drag (collisions with C^+ ions)? Models predict $\sim$ linear dependence of j_ν/n_H as a function of n_H (see Ali-Haïmoud et al. 2009). ⇒ search for carbon RRLs and correlate with continuum.
- Recoil momentum from H_2 formation? ⇒ search for kinematic signature in emergent H_2.

⇒ Need much more data!

Preliminary results from ATCA



Preliminary results from ATCA

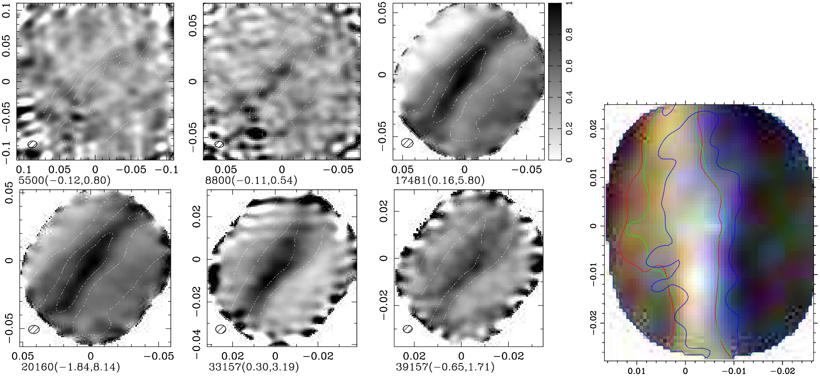
The matched beams at 8.8 GHz and 20.2 GHz allow placing limits on the spectral index ($F_\nu \propto \nu^\alpha$):

$$\alpha_{8.8}^{20.2} > 3.0 \text{ at } 3\ \sigma,$$

so we can rule out any thermal emission.

Does 20 GHz follow PAHs on 30 arcsec scales?

Surprisingly well in ρ Oph W, despite differences with S 1.

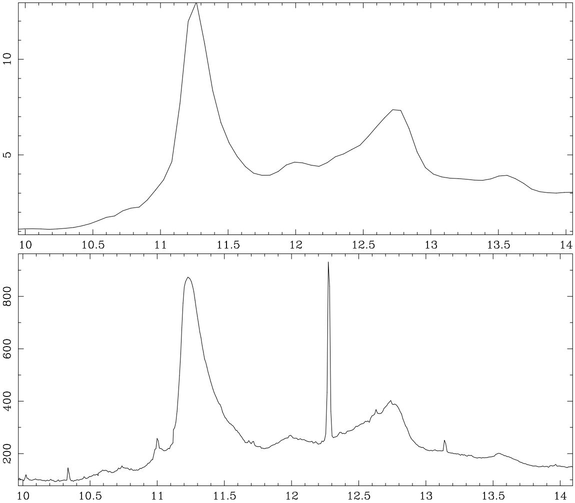


Simulated ATCA-IRAC 8μm contours overlaid on ATCA grey scale. Note spectral variations.

Search for C RRLs

- Pankonin & Walmsley (1978) missed ρ Oph W, but detected C90α and C91α from S 1.
- ρ Oph W: MOPRA 3 σ limits on C73α is 73 mJy beam^{-1} in a 30 arcsec beam (Casassus et al. 2008).
- ρ Oph W: ATCA CABB 3 σ limit on C71α, C72α and C73α is 6 mJy beam^{-1}.
- Expected C71α intensity is $\sim$1 mJy beam^{-1}....

An interesting datum: 31 GHz – H_2(0-0) correlation.



S1: top. ρ **Oph W**: bottom. Note H_2(0-0)S(2) at 12.278 μm.

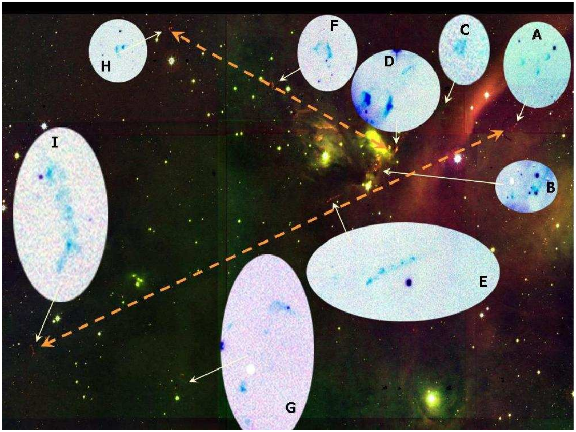
31 GHz – H_2(0-0)S(2) correlation: 2 points + origin.

	ρ Oph W	SR 3	S 1	S 1 off
H_2(0-0)S(2) [a]	2.9(-7)	1.9(-7)	$<$ 1.0(-8)	$<$2.7(-9)
I_{31GHz} [b]	2.2±0.2(-1)	1.4±0.2(-1)	$<$ 2.4(-2)	$<$1.8(-3)

[a] W m^{-2} sr^{-1}

[b] MJy sr^{-1}

UKIDSS H_2 mosaic.



WFCAM mosaic from `Lucas et al. (2008)`.

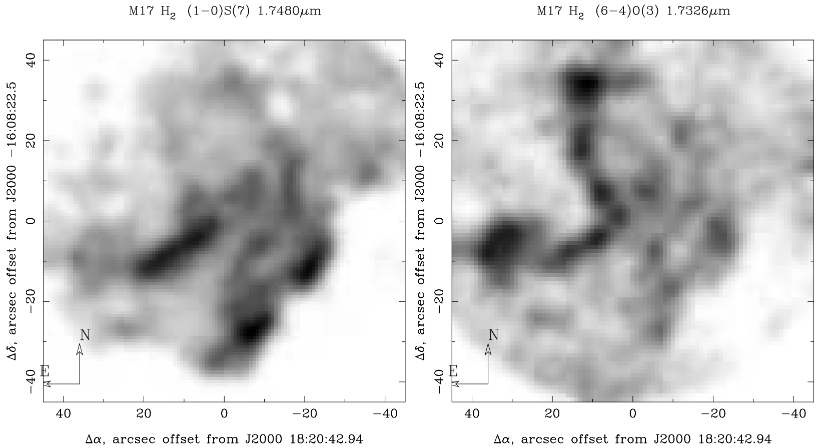
Origin of the H_2–cm-wave correlation

C^+ and fluorescent H_2 : The fluorescent H_2 layers in PDRs overlap with C^+ (e.g. Hollenbach & Tielens, 1997). *Plasma drag* spin-up is driven by the ions.

Spinning dust and formation pumping : Spin-up by the recoil of H_2 formation on VSG surfaces. H_2 production may be enhanced in regions of high VSG abundance. If so the H_2 near-IR spectrum should bear the signature of formation pumping.

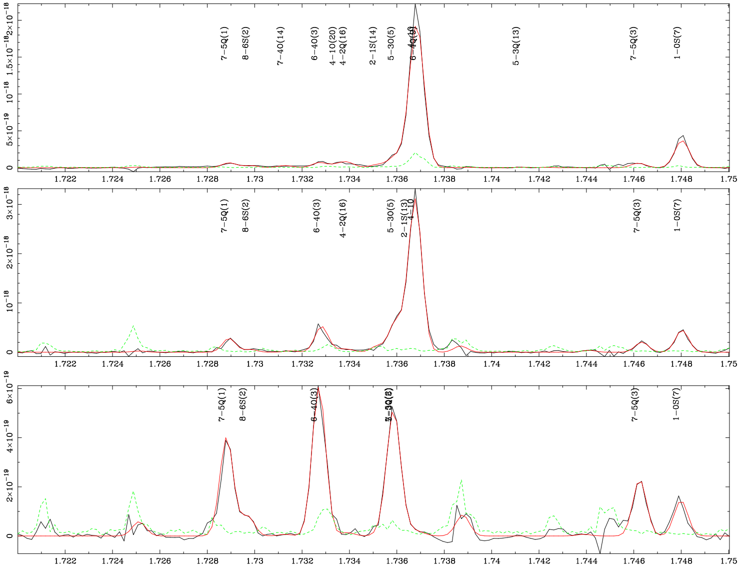
⇒ Test through near-IR area spectroscopy.

Tracers of H_2 formation pumping



FP data from Burton et al. (2002).

SINFONI H_2 spectroscopy



H_2 formation on VSGs

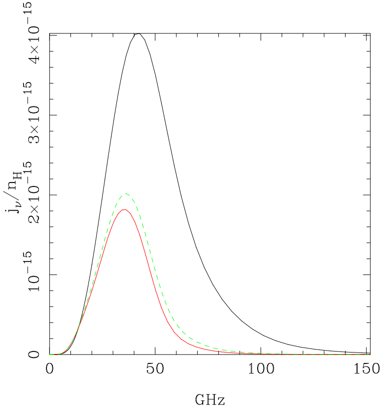
- The SINFONI spectroscopy confirms the line ratios from the FP data, in support of (6-4)O(3) as formation-pumped line.
- Spectrum of ρ Oph W exhibits highest H_2(6-4)O(3)/H_2(1-0)S(7)$\sim$2 $\Rightarrow$ formation pumping is very effective in ρ Oph W.
- $\Rightarrow$ Is the formation of H_2 exciting the rotation of VSGs in ρ Oph W?
- Same UV light dissociates and excites H_2: 1 in 15 electronic transitions lead to dissociation. So for dissociation balance in steady state, the lack of H_2 emission from S 1 implies that H_2 is not efficiently forming in S 1.

Rotational excitation by H_2 formation

- The reference model by Draine & Lazarian (1998) considers H_2 formation, but neglects it. Ali-Haïmoud, Hirata & Dickinson (2009) follow Draine & Lazarian for default H_2 parameters.
- However, choice of parameters is very uncertain:
  - The probably of formation per adsorbed H atom is taken $\gamma \lesssim 0.1$ from the average H_2 formation rate of Jura (1975). However, regions of 5–10 times higher formation rates have been found (Habart et al. 2004) $\Rightarrow \gamma \lesssim 1$?
  - The kinetic energy of emergent H_2 is taken as $E_F = 0.2$ eV, following Hunter & Watson (1978), but usual equipartition arguments in current PDR models take $E_F = 1.5$ eV.
- We can test the effect of enhancing E_F and γ using SPDUST (Ali-Haïmoud et al.). We absorb a factor of 10 in formation kinetic energy into γ, and compare spinning dust emissivities for $\gamma = 0,\ 1$, and 10.

SPDUST models with enhanced H_2 formation

Red, $\gamma = 0$ Green, $\gamma = 1$ Black, $\gamma = 10$.



Quick experiment with SPDUST (Ali-Haïmoud et al. 2009) supports that H_2 formation can dominate the rotational excitation.

Future & on-going work

- SINFONI constraints on the H_2 formation state, and incorporation into PDR (the Meudon code).
- Measure formation kinetic energy of H_2 through CRIRES spectroscopy of formation-pumped lines in rarefied medium.
- Test H_2–31 GHz correlation through wide-field H_2(1-0)S(1) HAWKI imaging.
- Constrain physical conditions in ρ Oph W through observations of the atomic/molecular content: C I / CO transition with CHAMP+ at APEX.

ALMA band 1

- Expected by 2014.
- 36–52 GHz. Not good for diffuse obs, perfect for compact obs if plasma-drag is dominant (because peak freq. rises with n_{H}).
- See `2009arXiv0910.1609J` for science case in protoplanetary disks.