Probing the hidden warm gas in protostellar outflows with *Herschel*

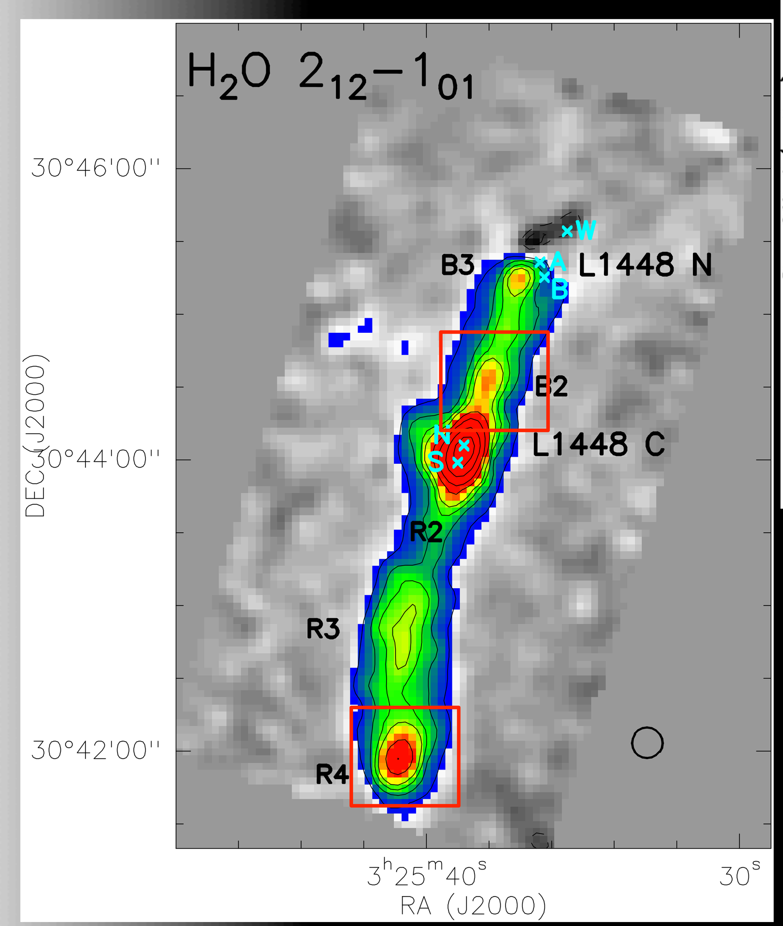
G. Santangelo[1], B. Nisini[1], S. Antoniucci[1], C. Codella[2], A. Lorenzani[2], T. Giannini[1], M. Benedettini[3], S. Cabrit[4], R. Liseau[5], M. Tafalla[6], E. F. van Dishoeck[7]

[1]INAF-Osservatorio Astronomico di Roma, Monteporzio Catone, Italy; [2]INAF-Osservatorio Astrofisico di Arcetri, Florence, Italy;[3] INAF-Istituto di Astrofisica e élanetologia Spaziale, Roma, Italy;[4]LERMA, Observatoire de Paris, Paris, France; [5]Chalmers University of Technology, Onsala, Sweden; [6]IGN Observatorio Astrònomico Nacional, Madrid, Spain; [7]Leiden Observatory, Leiden, The Netherlands

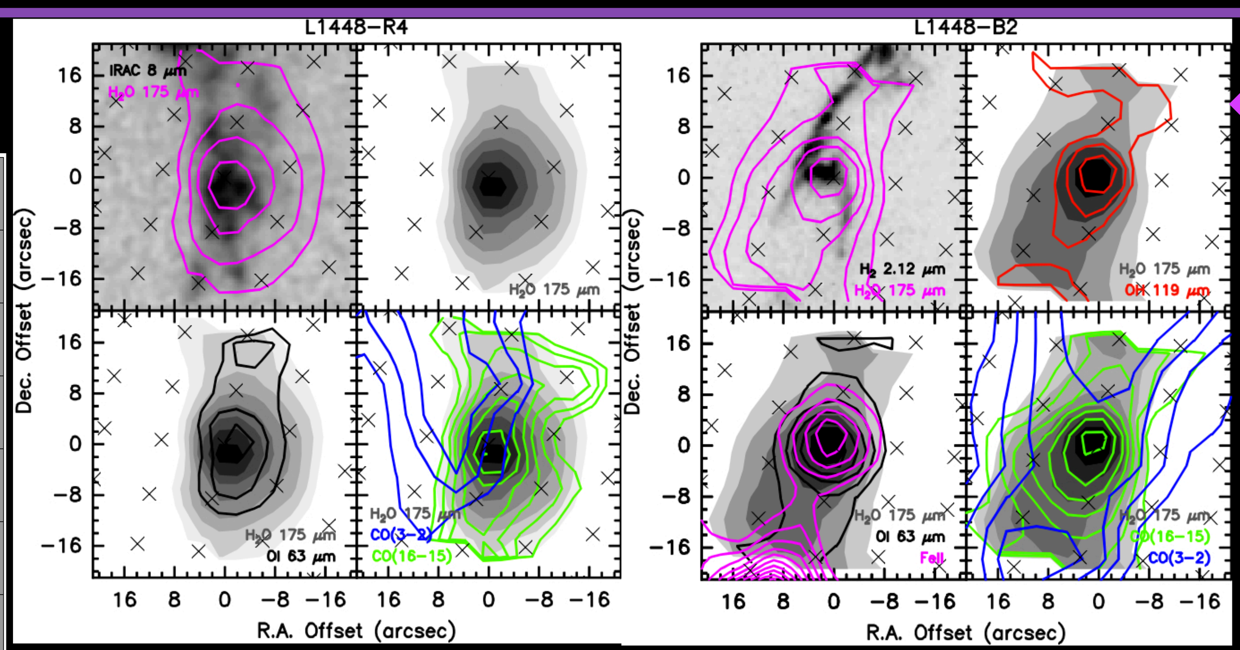
1. *Herschel* observations of outflows

Cooling of radiative shocks along the dense outflows driven by young protostars occurs through emission of mid- and far-IR lines of abundant species, such as H_2, CO, H_2O and [OI]. A detailed account for this emission has been only recently possible thanks to the space-born facilities like *Spitzer* and *Herschel*. **Multi-line *Herschel*-PACS and HIFI observations of several class 0 outflows** have been conducted as part of the Key Program WISH (Water In Star forming regions with *Herschel*, P.I. E. van Dishoeck) and of two guest observer programs (OT1_BNISINI_1 and OT2_GSANTANG_1). We present here some of the results obtained from these observations in the two well known outflows **L1448 and NGC1333-IRAS4**. In these outflows the spatial distribution of the different species is compared and the properties of the shocks at the origin of the observed emission discussed. In addition, we also present **maps of the [OI] 63μm line in several flows**, which reveal for the first time the presence of embedded fast atomic jets associated with the large scale outflows.

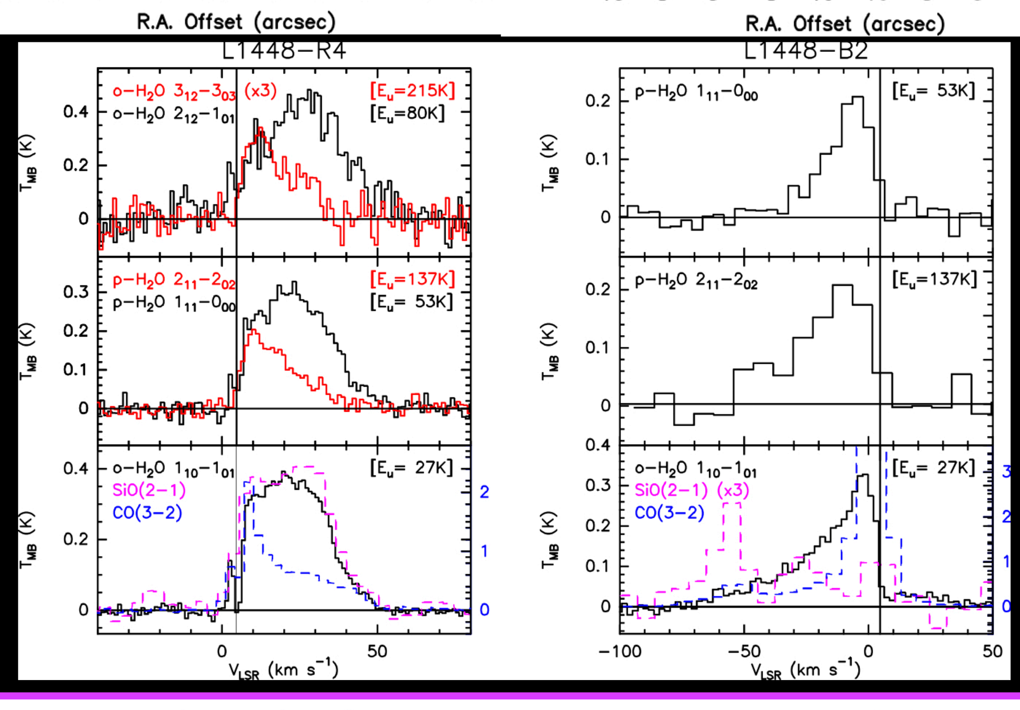
2. L1448



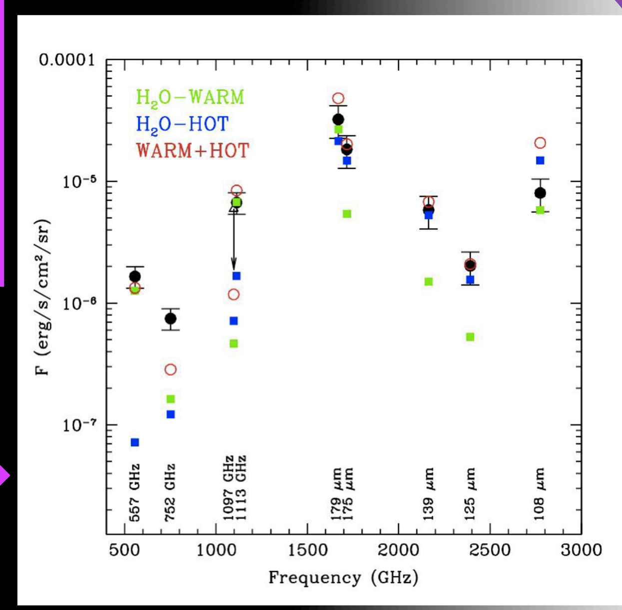
PACS H_2O 179μm map of the outflow from the class 0 source L1448-C. Water emission is detected along the flow direction with several peaks corresponding to the location of on-going shock interactions. Note the **strong peak at the L1448-C source location**, and, conversely, the absence of emission at the location of the L1448-N cluster of sources, due to H_2O photo-dissociation from the local UV field (from Nisini et al. 2013, A&A, 549, 64). **A detailed multi-wavelength analysis has been performed on the R4 and B2 shock positions** (Santangelo et al. 2012, A&A, 538, 45; 2013, A&A in press).



The **PACS map of the H_2O 3_{03}-2_{12} line** is compared with different lines detected towards the L1448-B2 and R4 positions. From the upper left panels, clockwise: H_2 from *Spitzer*-IRAC 8μm (in R4, Tobin et al. 2007, ApJ, 659, 1404) and at 2.12μm (in B2 Davis & Smith, 1995, ApJ, 443, 41); OH 119μm (detected only in B2); CO(16-15) and CO(3-2); [OI] 63μm and [FeII] 26μm (detected only in B2, from Neufeld et al 2009, ApJ, 706, 170).



HIFI line profiles of H_2O transitions detected in the L1448-R4 and B2 positions. In the R4 position, lines at different excitation (E_u indicated in the figure) present very different profiles, with the fundamental ortho- and para-H_2O transitions showing a clear excess at high velocity. In the bottom panels the H_2O is compared with CO(3-2) and SiO(2-1) lines: the profiles are different, showing that water traces a different gas component with respect to the ground-base observed transition.



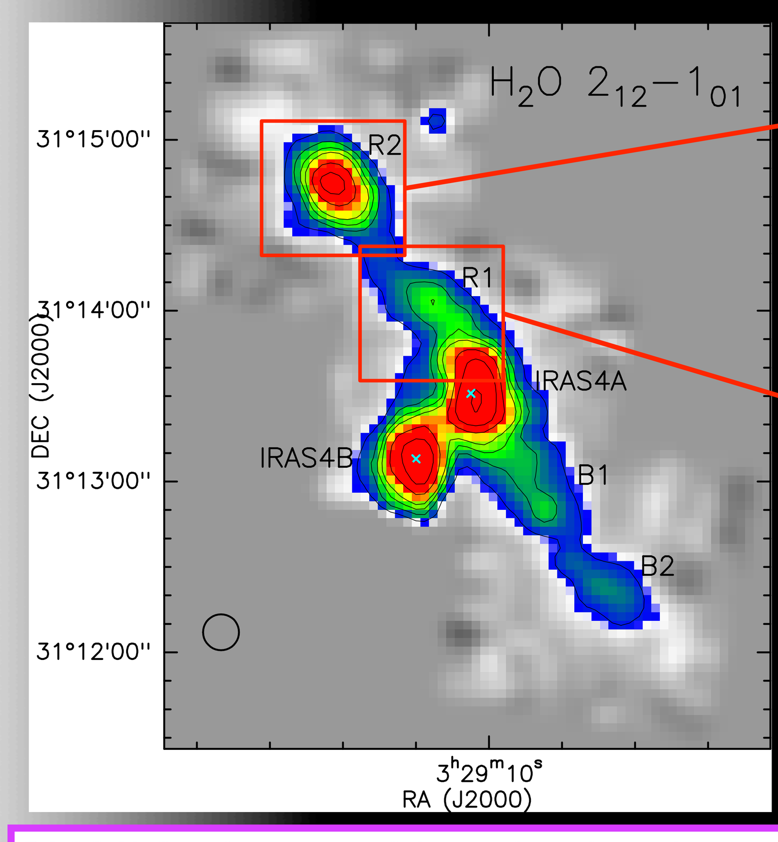
Flux of the **water lines observed in L1448-B2** (black circles) **compared with a two gas component model**: a warm and diffuse component (T_{kin}=450 K, $n(H_2)$=10^6 cm^{-3}, $N(H_2O)$ = $3x10^{14}$ cm^{-2}) and a hot and compact component (T_{kin}=1100 K, $n(H_2)$=$5x10^5$ cm^{-3}, $N(H_2O)$ = $2x10^{16}$ cm^{-2}). The sum of the two models is reported as red symbols.

SUMMARY OF RESULTS

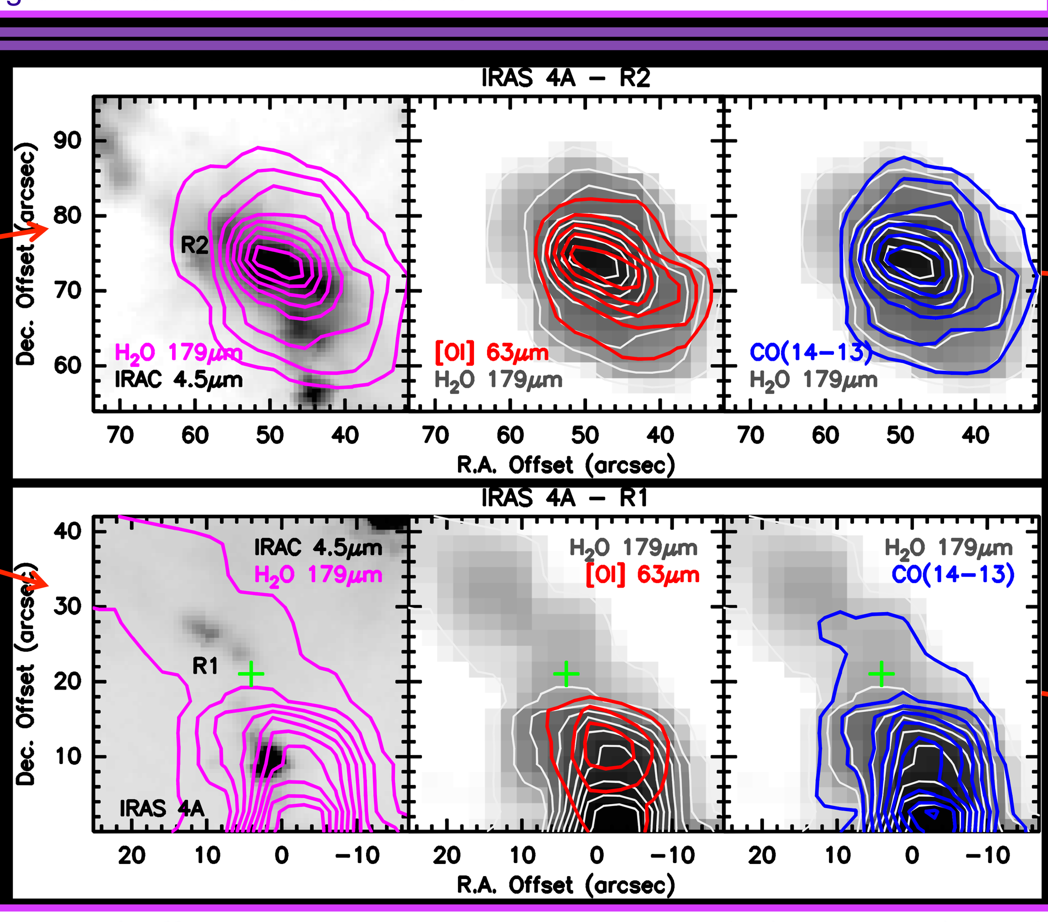
The results from the analysis of the HIFI and PACS observations in the B2 and R4 shock positions can be summarized as follows (Santangelo et al. 2012, 2013):

- The H_2O profiles and spatial distribution show that **water probes gas components different from the 'standard' outflow gas traced by low-*J* CO and SiO emission**.
- H_2O is instead associated with the same **high pressure shocked gas** (T_{kin} > 300 K, $n(H_2)$ > 10^5 cm^{-3}) that emits in the mid-IR H_2 lines and in the high-*J* (*J*>14) CO lines.
- A combined analysis of the H_2 (from Spitzer), high-*J* CO and H_2O line emission shows that **at least two gas components are needed to reproduce the full set of observations**: a warm (T_{kin} ~ 500 K) rather extended component, and an hot (T_{kin} ~ 1000 K) and compact component. The former may represent gas associated with older shock episodes, already cooled down with timescales of few thousands of years, while the latter is associated with presently undergoing shocks.
- The emission at the **B2** position (the apex of a bow-shock), is consistent with **partially dissociated gas excited in a low-velocity *J*-shock** (as also testified by the detection of OH emission), while the emission at the **R4** position is better explained by a **non-dissociative C-shock**.

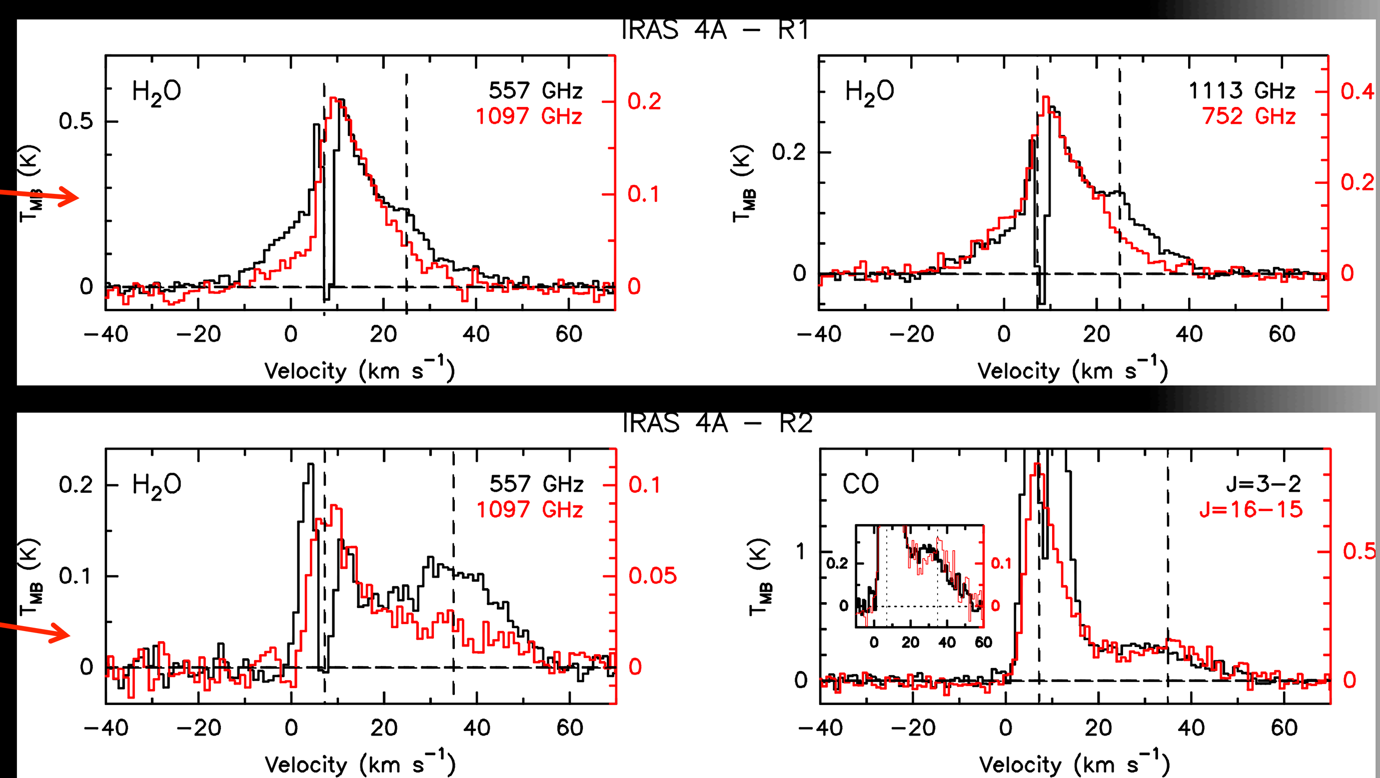
2. NGC1333-IRAS4



PACS H_2O 179μm map of the outflow from the class 0 sources NGC1333-IRAS4A and IRAS4B. Similarly to L1448-C, strong emission is observed on the two sources and at the terminal shock R2.



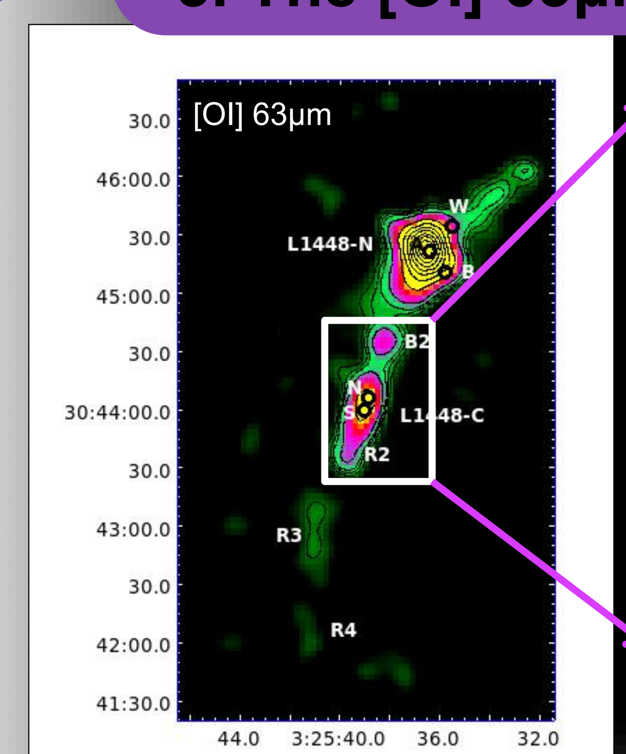
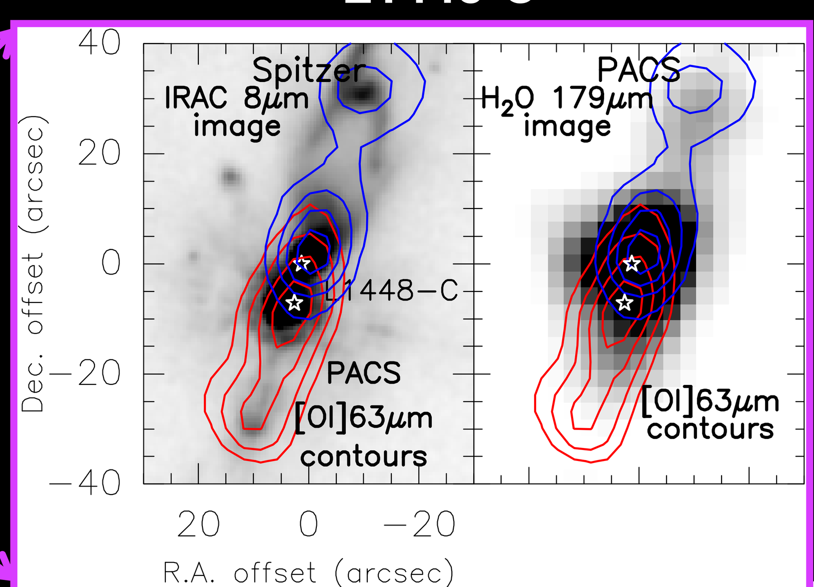
PACS maps of different lines in the two shock positions R1 (upper panel) and R2 (lower panel). The H_2O 179μm line is overlaid on a *Spitzer* IRAC image on the left panels. In the central and right panels, the [OI] 63μm and the CO(14-13) lines are compared with the water map. Note that while in the shock far from the central source (R2) the different tracers peak at the same position, a clear displacement between [OI] and H_2O is seen close to the source, pointing to a different chemistry at the outflow base (see also section below).



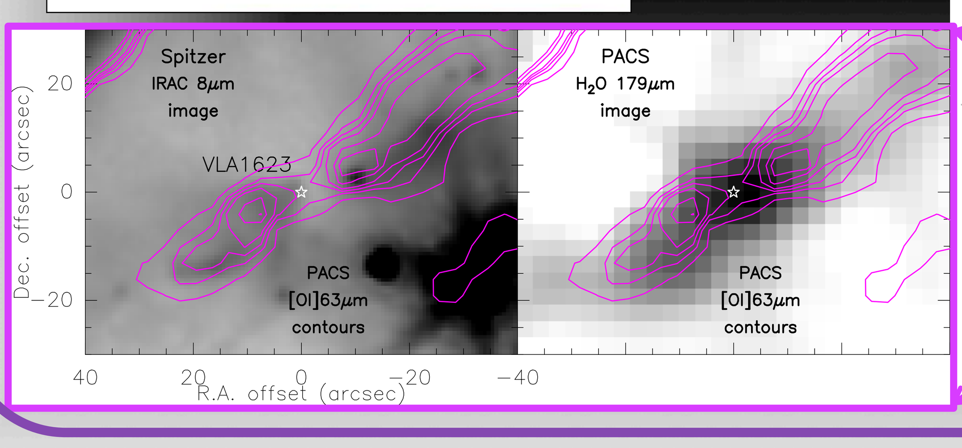
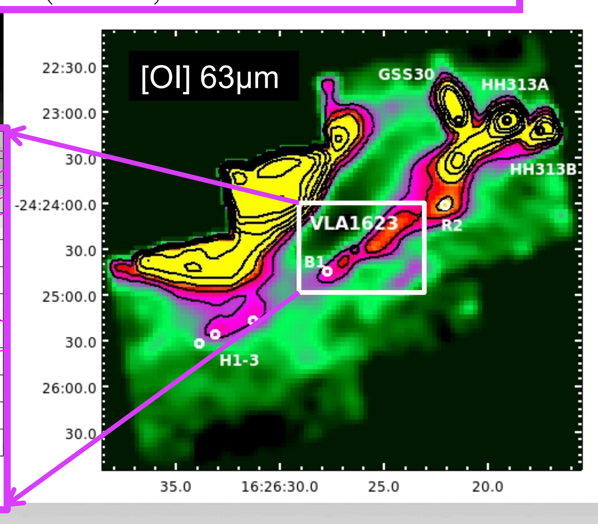
HIFI profiles of H_2O lines with different excitation energies in the two shock positions R1 (upper panel) and R2 (lower panel). The specra are convolved at a common resolution of 38''. Similarly to the case of L1448-R4, the ground state transitions of ortho and para H_2O (557 GHz and 1113 GHz) lines show, in both positions, an excess of emission at high velocity. CO(16-15) shows the same secondary emission peak at about 35 km/s, which is shifted towards lower velocities in the CO(3-2) profile.

3. The [OI] 63μm jets

L1448-C

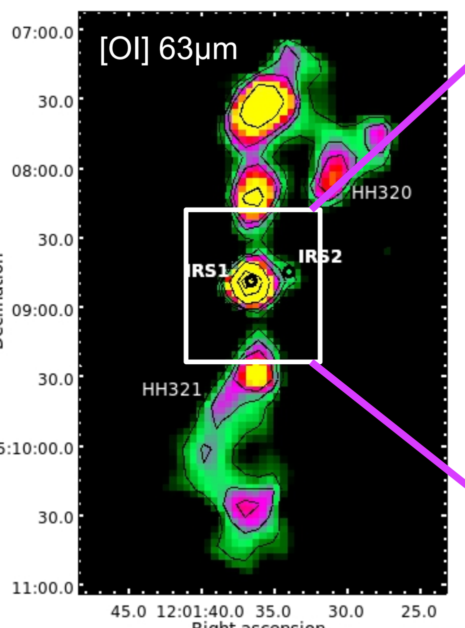
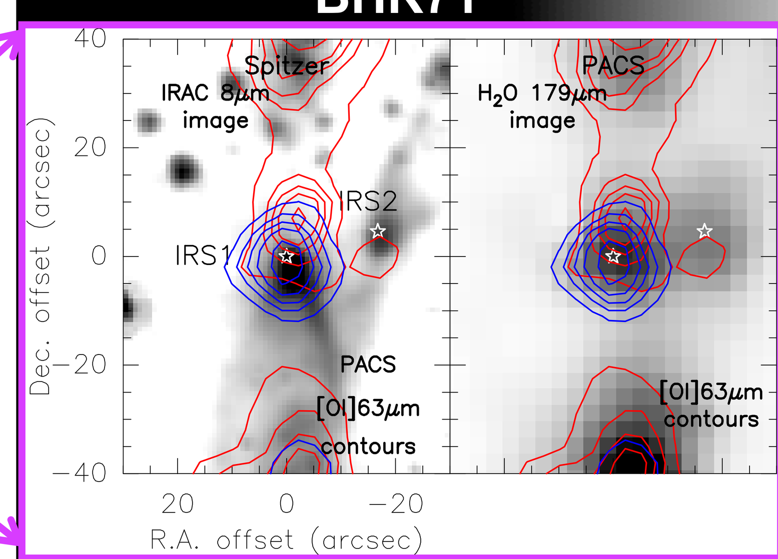
VLA1623

[OI] 63μm PACS maps of several class 0 outflows. These maps **reveal for the first time atomic emission associated with the collimated jet** at the outflow base. The PACS spectral resolution (R ~ 5000) is sufficiently high to **resolve the blue- and red-shifted emission in the jets** travelling at the highest speed (namely L1448 and BHR71, where v_r > 100 km/s).

There is **no clear spatial association between the [OI] and the H_2O emission at the outflow base**: while [OI] traces prevalently the collimated jet, with emission peaks along the jet axis and symmetrically displaced with respect to the central source, water is centrally peaked and localized closer to the source. This indicates that the **internal shocks giving rise to the [OI] line emission are highly dissociative**.

BHR71

NGC1333-IRAS4