Characterizing the PBRS: A *Herschel*-detected Sample of The Youngest Protostars in Orion

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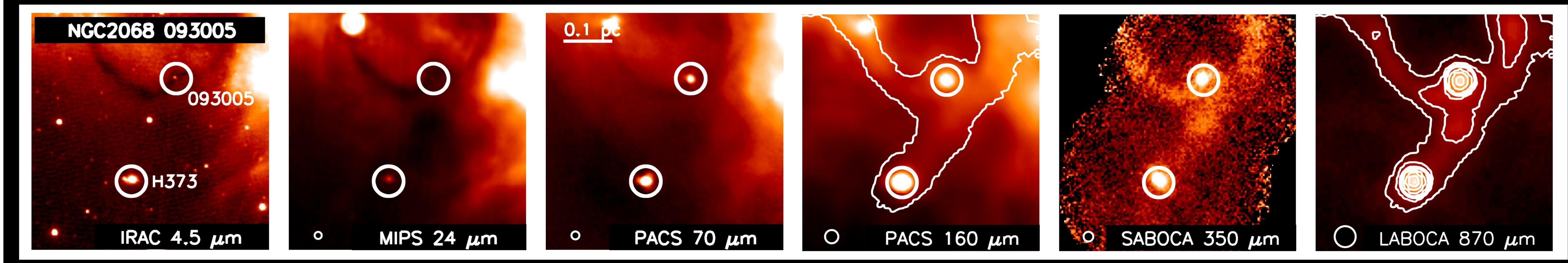

We have detected a sample of the reddest, and likely youngest, protostars in the Orion molecular clouds using PACS observations from the *Herschel Space Observatory* as part of the *Herschel* Orion Protostar Survey (HOPS). We find 19 sources (12 of which are *Herschel*-only detections) that have extremely red 24 μm to 70 μm colors (Figure 1). We refer to these sources as the "PACS Bright Red sources", or PBRS. Stutz et al. (2013) concluded that the red colors of the PBRS (Figure 1) are best explained by high envelope densities, the highest Class 0 envelope densities of all the observed protostars in Orion. To further characterize these the PBRS, we have now obtained follow-up CARMA 2.9 mm continuum and CO (J=1-0) maps toward 14/19 PBRS, in addition to *Herschel* PACS spectroscopy toward 8/19 PBRS.

Key Results

- CARMA observations show that the PBRS have the highest ratio of 2.9 mm luminosity to L_{Bol} when compared to protostars in nearby star forming regions (Figure 2). This is further evidence that they have very dense envelopes and are in a very early stage of protostellar evolution.
- Both flat and declining 2.9 mm visibility profiles are found. The flat profiles require either an unresolved component and/or a very steep density law ($\rho \propto R^{-2.5}$), see Figures 3 and 4.
- The PBRS with flat visibility profiles are systematically less luminous than those with declining profiles (Figure 2). If protostars become more luminous with evolution (as expected), then the visibility profiles may evolve from flat to rapidly declining. The flat visibility profile sources could be undergoing a period of brief, rapid infall.
- CO (J=1-0) outflows are detected toward 10/14 of the PBRS, including both compact and extended outflows. The emission morphologies show that most of the outflows are inclined, and that the PBRS are at intermediate inclinations. This implies that the very red colors and cold T_{bol} values must be due to dense envelopes, and not an edge-on inclination (Figure 5 and Table 1).
- *Herschel* PACS spectroscopy detects far-IR CO and water emission lines toward 5/8 observed PBRS. The average Far-IR CO rotation temperature for the PBRS is 233 K, below the typical 300 K and possibly suggesting colder shock conditions (Figure 6, Table 1).

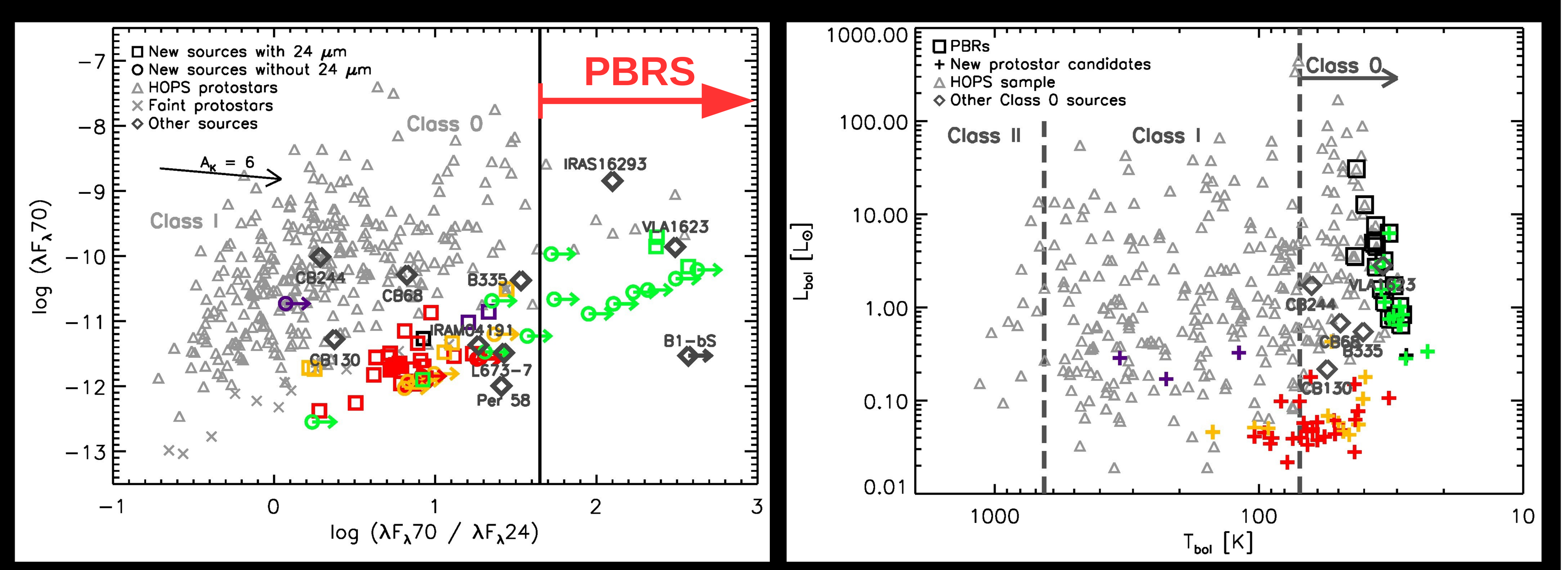

Figure 1: Plots showing the extreme characteristics of the PBRS compared to other Orion protostars and well studied protostars in other clouds. Both panels show the sample of HOPS protostars detected at 70 μm; the green symbols show the PBRS (and other 'new' sources) and the black diamonds are well known protostars from other clouds. The left panel shows the color selection criteria of the PBRS. The right panel shows that PBRS appear to be extreme Class 0 objects, with similar luminosities but systematically colder T_{bol}. The rarity of the PBRS suggest they have lifetimes of only ~25,000 years, 5% of the protostellar lifetime (Stutz et al. 2013).

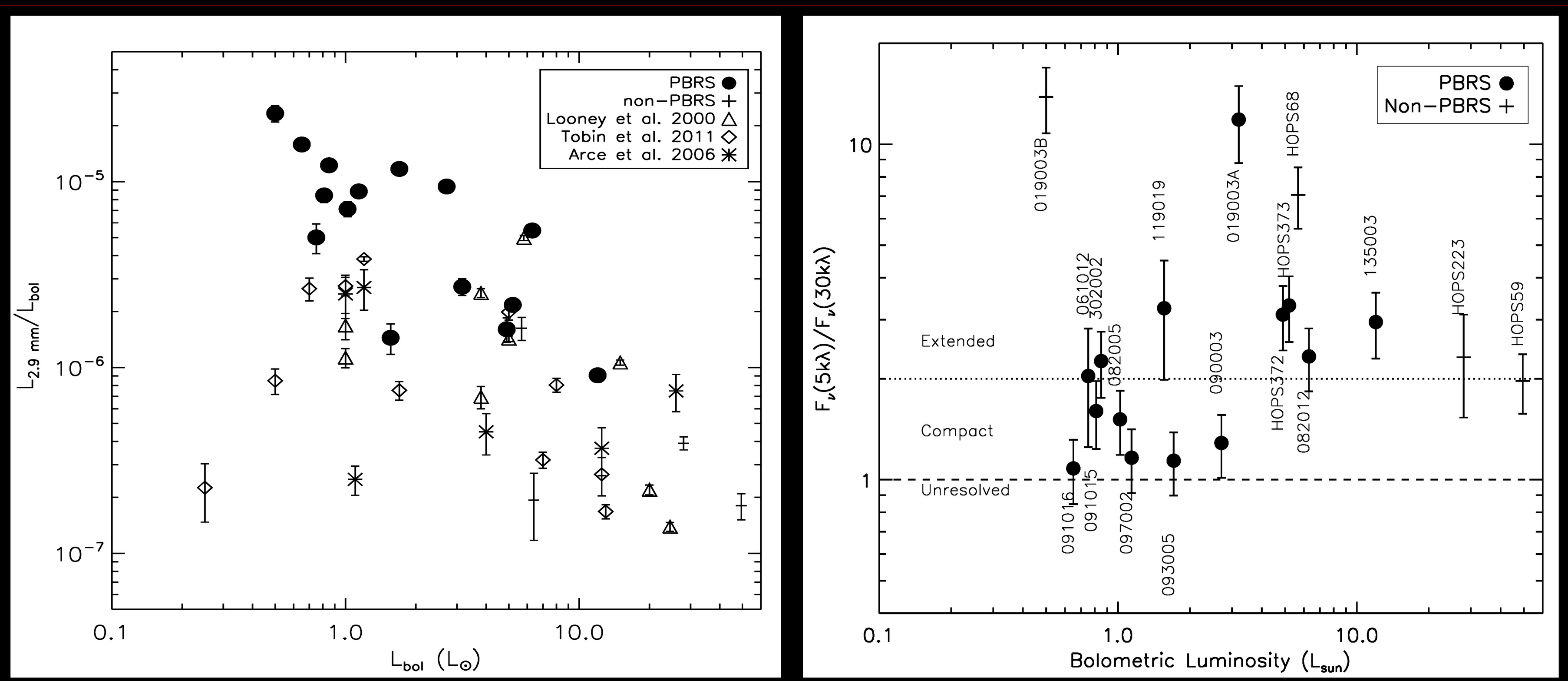

Figure 2: Properties of PBRS at 2.9 mm. The left panel shows the fraction of luminosity at 2.9 mm vs. L_{bol}. For a given L_{bol}, the PBRS have the greatest or greater 2.9 mm luminosities than typical Class 0 protostars drawn from the literature. The right panel shows the ratio of the visibility amplitudes at 5 kλ (17,000 AU) to 30 kλ (3,000 AU). The lowest luminosity PBRS tend to have ratios between 2 and unity, meaning that the bulk of their 2.9 mm emission is originating from scales smaller than 3,000 AU. This is indicative of massive, compact structure and/or steep envelope density profiles toward these sources.

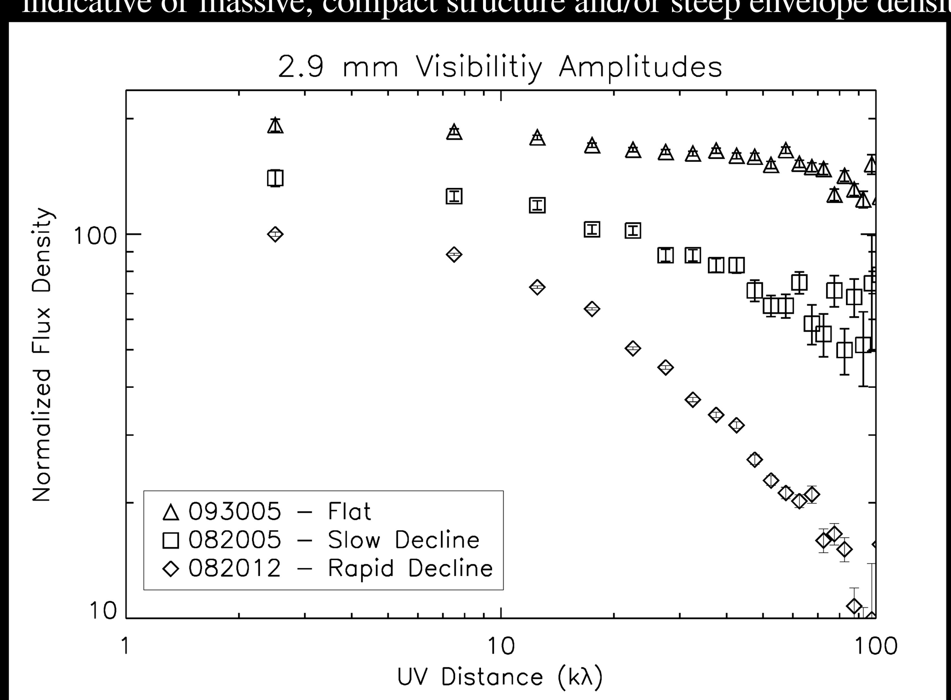

Figure 3: Visibility amplitude profiles representative of the variation seen in the PBRS sample. We propose that the sources with flat and slowly declining visibility amplitudes are the youngest and possibly undergoing a brief period of rapid infall.

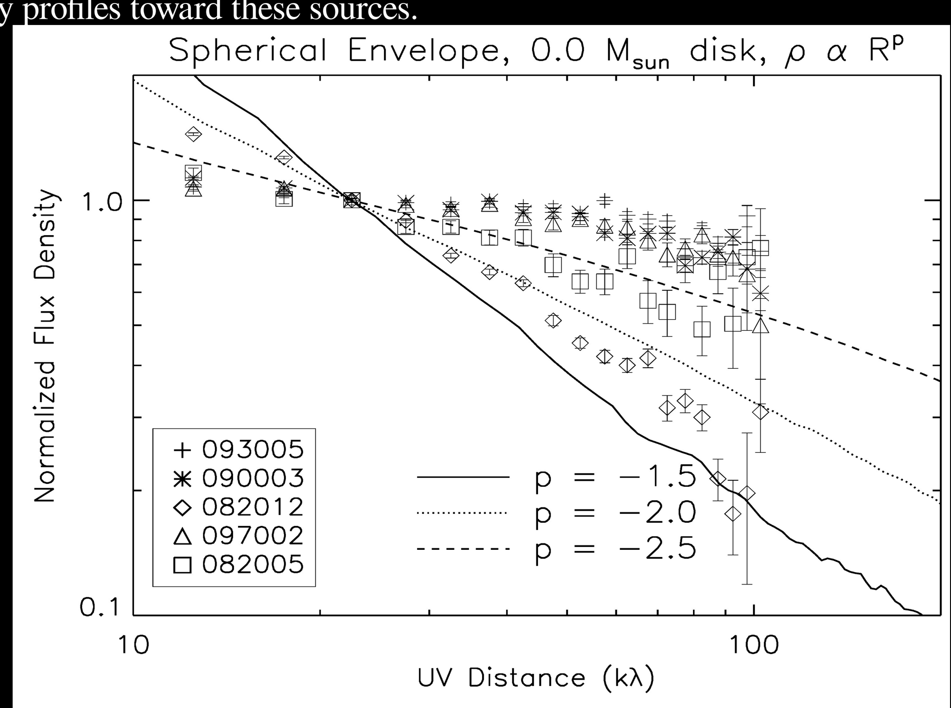

Figure 4: PBRS visibility amplitudes compared to spherical envelope density profiles. Without an additional compact source the PBRS with flat visibilities are most consistent with p= -2.5.

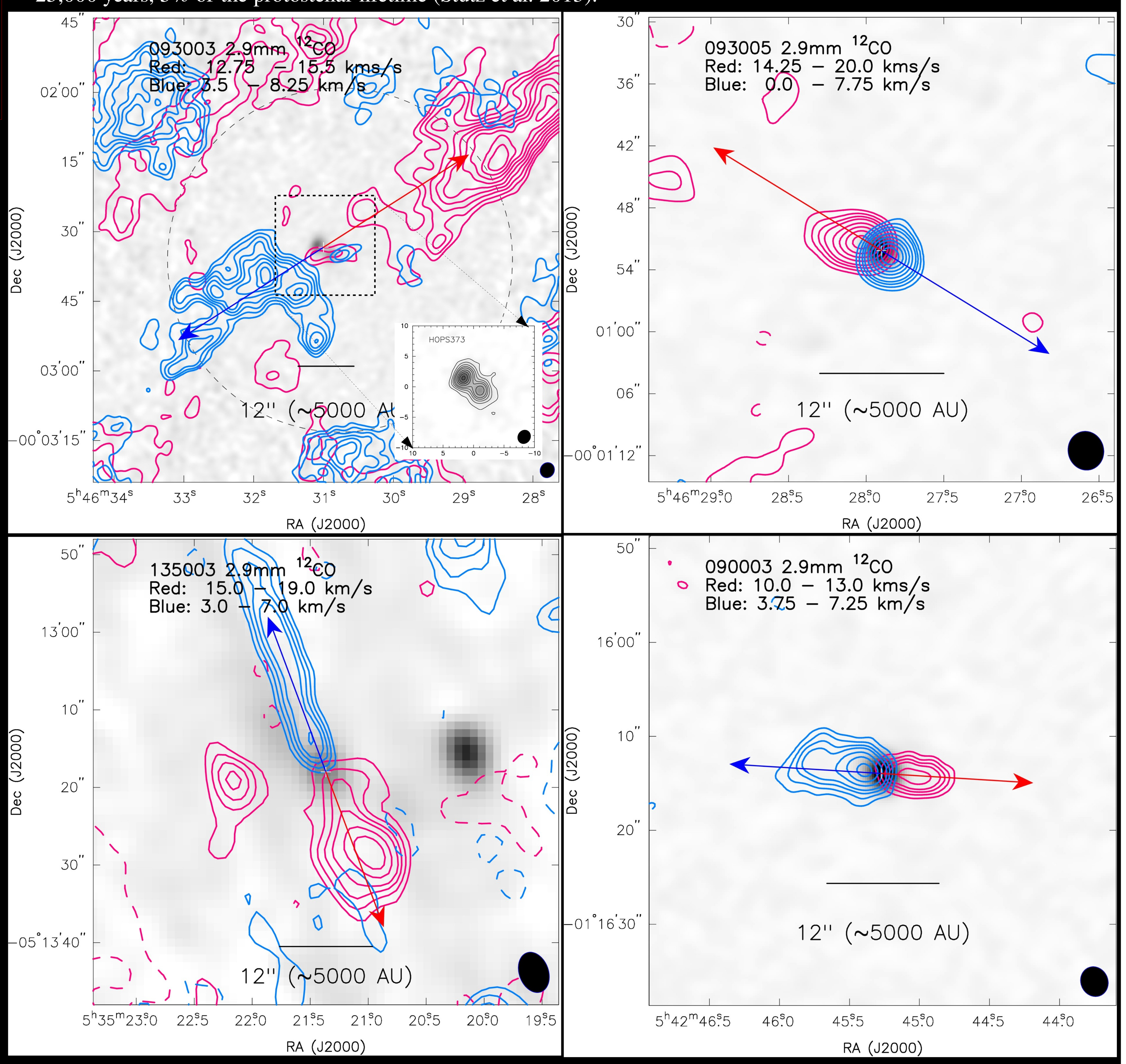

Figure 5: Plots of CARMA CO (J=1-0) contours overlaid on the 2.9 mm continuum images. The *top left* shows HOPS373/093003, a binary PBRS with a wide, extended outflow along with possibly a compact outflow from the secondary. The *top right* shows 093005 (the reddest PBRS) to have a compact CO (J=1-0) outflow. The *bottom right* shows 135003 having a jet-like blue-shifted outflow while the red-shifted side is wider. The *bottom right* shows 090003 another source with a compact outflow, like 093005. Both 093005 and 090003 have very flat visibility amplitudes and compact outflows. The flat visibility amplitudes found toward sources with compact outflows and sources without detected outflows are suggestive of the youthful nature of these sources. Both HOPS 373/093003 and 135003 have more well-developed outflows and declining visibility amplitudes.

PBRS	Visibilities	Outflow	PACS Lines	CO Trot	F(3 mm)
091016 – HOPS 402	Flat	Not Det.	Not Det.	-	46.6 mJy
091015 – HOPS 401	Slow Decline	Not Det.	Not Det.	-	30.9 mJy
082005 – HOPS 398	Slow Decline	Not Det.	SOFIA		32.9 mJy
097002 – HOPS 404	Flat	Not Det.	Not Obs'd		45.7 mJy
093005 – HOPS 403	Flat	Compact	Detected	212 K	90.0 mJy
090003 – HOPS 400	Flat	Compact	SOFIA		115 mJy
082012 – HOPS 399	Rapid Decline	Extended	SOFIA		156 mJy
093003 – HOPS 373	Rapid Decline	Extended	Detected	284 K	51.1 mJy
302002 – HOPS 407	Rapid Decline	Extended	Not Obs'd		47.1 mJy
135003 – HOPS 409	Decline + Flat	Extended	Detected	220 K	49.3 mJy
119019 – HOPS 405	Rapid Decline	Extended	Detected	207 K	10.2 mJy
019003 – HOPS 394	Rapid Decline	Compact?	Detected	241 K	38.9 mJy
061012 – HOPS 397	Rapid Decline?	Extended?	Detected?	-	17.0 mJy
HOPS 372	Rapid Decline?	Extended	Not Obs'd		35.6 mJy

Table 1: List of sources and characteristics observed with CARMA and the PACS Spectrometer.

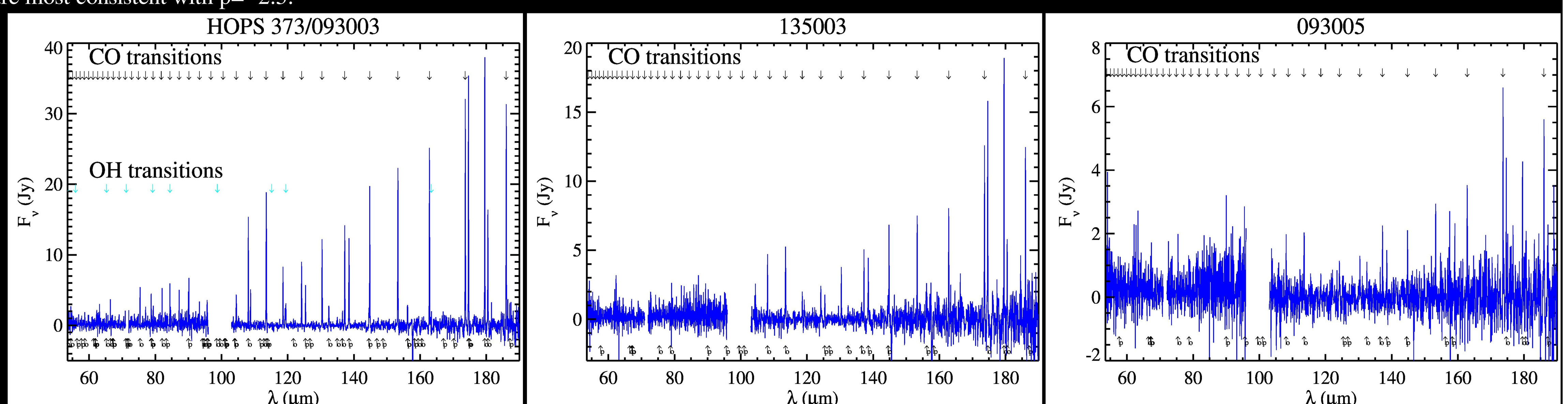

Figure 6: Plots of the PACS spectra toward three of the 5/8 PBRS with definitive CO/water line emission; the CO (J=1-0) outflows of these three sources are shown in Figure 5. The far-IR spectrum of HOPS 373/093003 (*left*) is quite spectacular, detecting very high excitation water, CO, and OH transitions; this is the richest line spectrum toward a PBRS. The *middle* shows 135003, this source was the second brightest in our sample and one of only two with CO and water emission extended across multiple spaxels (the other is 019003). The *right* spectrum is 093005, the reddest PBRS. Despite having overall fainter line emission, both CO and water lines are detected. The sources without detected CO (J=1-0) outflows did not have detected PACS lines. The arrows in the bottom of each image mark water transitions with corresponding to ortho (o) and para (p).

References:
Stutz et al. 2013, ApJ, 767, 36
Tobin et al. 2014, ApJ, in press.

HERSCHEL ORION PROTOSTAR SURVEY