Massive Jets from High-Mass YSOs

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Summary

Protostellar jets from high-mass young stellar objects (HMYSOs; $M \geq 8\ M_\odot$) provide an excellent opportunity to understand the mechanisms responsible for high-mass star formation. However, the sample of known high-mass protostellar jets is still limited and the jet physical properties are not well known. We present our ongoing near-infrared imaging (H_2, 2.12 µm) and spectral (1-2.5 µm) survey of jets from a sample of HMYSOs. By using H_2 narrow-band imaging (Sofi/NTT, NICS/TNG), we aim at verifying the shocked nature of 120 EGOs (Extended Green Objects) detected with Spitzer (Cyganowski et al. 2008), because the EGO origin is not clear (e.g. Takami et al. 2012). Among these 120 EGOs, we indentify jets/outflows with a 44% success rate (Stecklum et al. 2009). In addition, several jets/outflows from previously unknown HMYSOs were detected in this survey (Stecklum et al. in prep.). The morphology of the H_2 emission generally differs from that of the 4.5 µm excess, suggesting different excitation conditions. Through IR low-resolution spectroscopy (Sofi/NTT, R~600) we also derive the physical properties of 16 bright massive jets (Caratti o Garatti et al. in prep.), relating them with those of their driving sources (with L_{bol}~10^2-$10^5\ L_\odot$). As for the low-mass jets (Caratti o Garatti et al. 2006, 2008), we derive a clear correlation between the HMYSO bolometric luminosity (L_{bol}) and the jet H_2 luminosity (L_{H2}), extending this relationship over 6 order of magnitudes in the L_{bol} range (from 0.1 to $10^5\ L_\odot$).

Selected Observational Results...

G 35.20-0.74 N

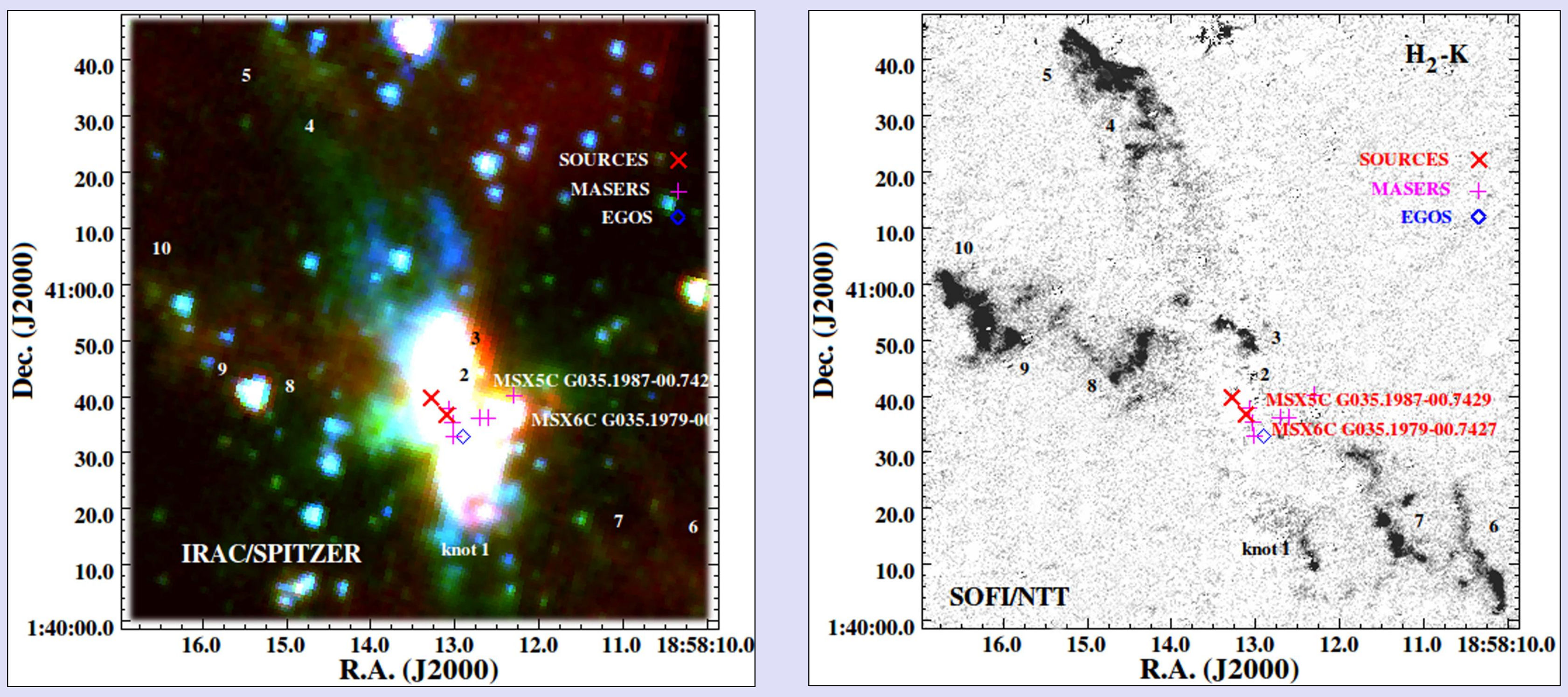

Figure 1: Tricolor Spitzer image (3.6 - 4.5 - 8 µm) **(left)** and H_2 (2.12 µm) continuum subtracted image **(right)** of the G35.2 N region. The H_2 image shows two precessing jets driven by the high-mass binary system (Sánchez-Monge et al. 2013). Source, maser and EGO positions are also indicated in the figures.

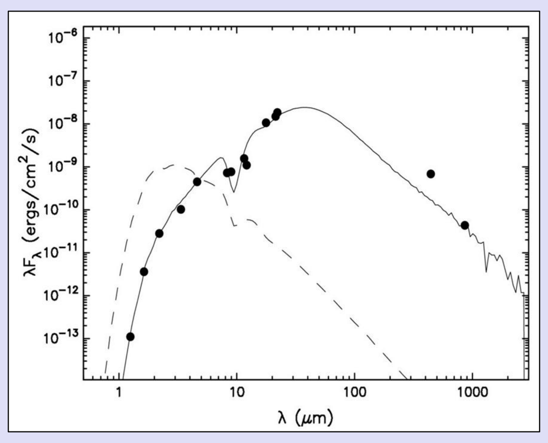

Figure 2: SED and its best-fitting model for G 35.2 N, derived by using the radiative transfer model in Robitaille et al. 2007. The photometric data points were collected from the literature. Some values from the fit: $L_{bol} = 1.7\times10^4\ L_\odot$, $M_{env} = 3\times10^3\ M_\odot$, $M_* = 17\ M_\odot$.

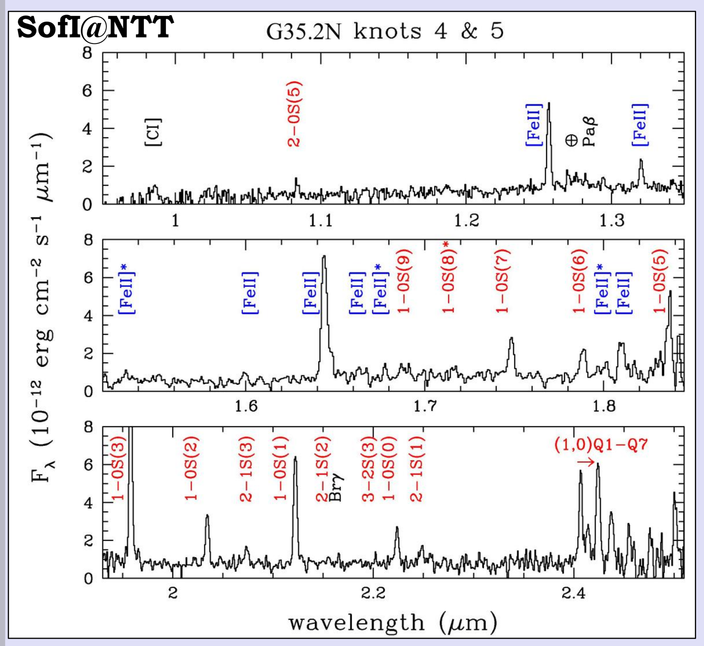

Figure 3: NIR spectrum of knots 4 and 5 in the G35.2 N jets: ionic ([FeII], [CI], HI) and molecular (H_2, v ≤ 2) features are visible.

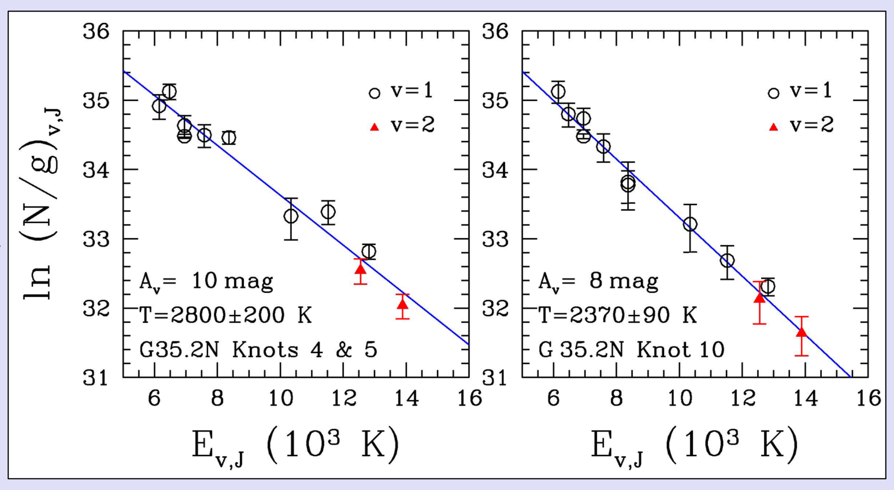

Figure 4: H_2 ro-vibrational diagrams of two shocked regions of the G35.2 N jets. The blue line indicates the best fit to the different H_2 lines, providing gas temperature, column density, and visual extinction.

MSX G326.47+00.69

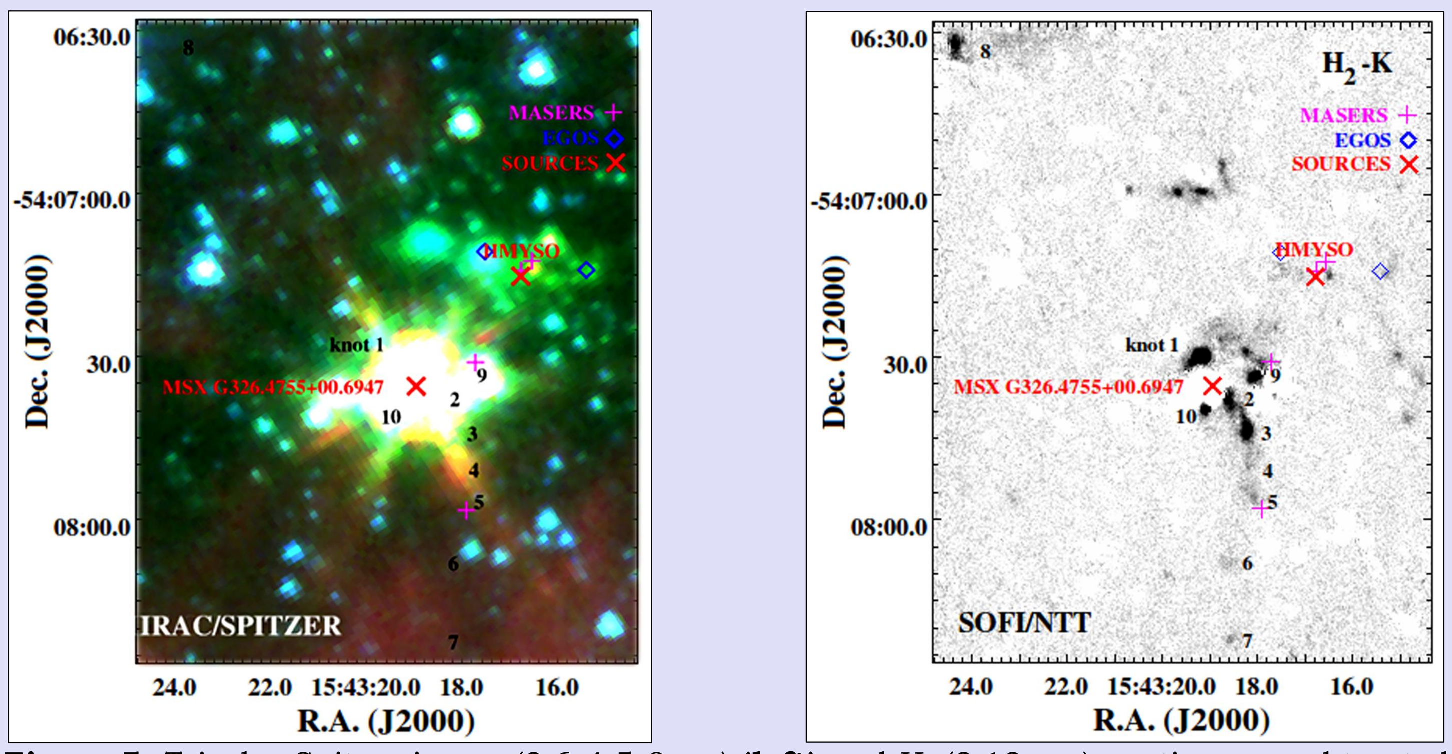

Figure 5: Tricolor Spitzer image (3.6-4.5-8 µm) **(left)** and H_2 (2.12 µm) continuum subtracted image **(right)** of the G326.47+00.69 region. The H_2 image show a precessing jet driven by the high-mass MSX source in the centre. Another jet is visible NW from the source, driven by a (previously unknown) HMYSO. Notably, the EGO emission (in green) does not match the H_2 emission. Source, maser and EGO positions are also indicated in the figures.

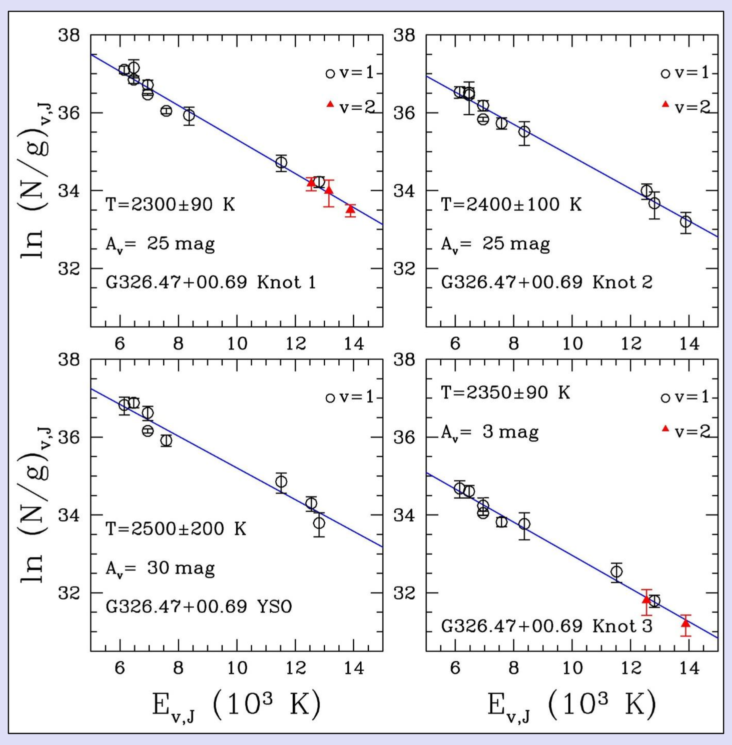

Figure 6: H_2 ro-vibrational diagrams of four knots of the G326.47+00.69 jet. The blue line indicates the best fit to the different H_2 lines, providing gas temperature, column density, and visual extinction.

...& Overall Findings

Imaging & Spectroscopy

- A wiggling morphology is observed in most of the massive collimated H_2 jets (see Fig.1 & 5), often with large precessing angles up to 40° (larger than in low mass YSOs), suggesting that dynamical interactions among massive stars are stronger and more frequent than in low-mass star-forming regions. The complex dynamics can explain the confused H_2 morphology often observed and the lack of collimation in several massive outflows.

- The NIR spectra are similar to those of low mass YSOs, showing low excitation conditions (Fig. 3). Several H_2 lines dominate at NIR wavelengths, coming from low and high excitation energy levels. Ionic emission is frequently observed ([FeII] is detected in 9 out of 16 targets).

- No evidence of fluorescent emission along the jets: the H_2 line ratios of different vibrational levels indicate collisional populations (e.g. Fig.4 & 6).

Physical observables

- High visual extinction towards knots close to the sources (A_v up to 60). Average A_v is much larger than in low-mass jets. Observed trend along the jets: A_v decreases from the source towards the jet terminal bow-shocks.

- From the H_2 ro-vibrational diagrams (Fig. 4 & 6) we obtain the H_2 temperature (T_{H2}) and the column density of each knot (T_{H2} from 2000 K to 5000 K, N_{H2} ~10^{17}-10^{20} cm^{-2}).

- On average, T_{H2} and N_{H2} are larger than in low-mass jets.

- Combining imaging and spectroscopy, we compute the total H_2 mass (M_{H2}, from N_{H2} and emitting area), as well as the total H_2 luminosity (L_{H2}, by means of temperature and extinction), which provides an estimate of the jet radiated flux. The derived values are 1-2 orders of magnitude higher than those in low mass jets (Fig.7).

- High-mass jets in the NIR are scaled-up versions of their low-mass counterparts: they show same emission lines, but the derived physical parameters are larger.

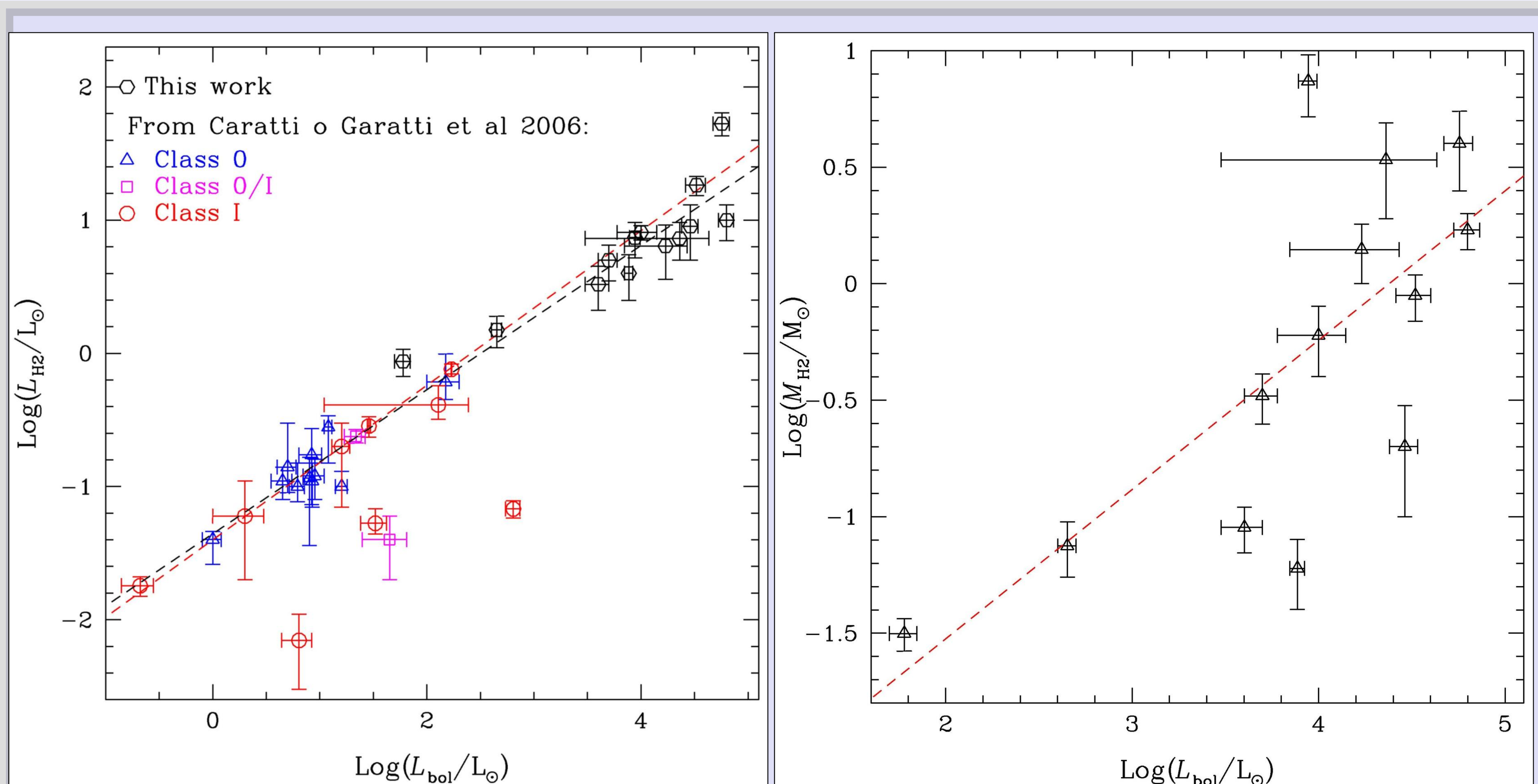

Figure 7. *Left:* L_{H2} (jet) vs L_{bol} (source). The plot combines data from low-mass jets (Caratti o Garatti et al. 2006; blue, red and magenta symbols) with those analysed in this work (in black). The red dashed line indicates the best fit obtained in the 2006 paper ($L_{H2} \propto L_{bol}^{0.58}$), and the blue line shows the new fit ($L_{H2} \propto L_{bol}^{0.55}$) derived combining the whole sample. ***Right:*** M_{H2} (jet) vs L_{bol} (source) for the high-mass jet sample. Although there is not a straightforward relationship, the M_{H2} of jet increases with the L_{bol} of the source.

The energy budget

L_{H2} vs L_{bol}

To compare the jet energetics in low and high mass YSOs, we relate the source bolometric luminosity (L_{bol}) with the H_2 jet luminosity (L_{H2}). A correlation between these two quantities is expected if L_{bol} is dominated by the accretion luminosity and if accretion and ejection of matter are strictly related.

In a previous study (Caratti o Garatti et al. 2006) we derived a linear correlation between L_{bol} and L_{H2} for a sample of jets from Class 0 and I low-mass YSOs, which holds also for jets from HMYSOs (Fig.7, left).

M_{H2} vs L_{bol}

We also compare the inferred mass of the H_2 jet with the HMYSO bolometric luminosity, which should be proportional to the mass of the central engine (Fig. 7, right). Despite the large scattering, the M_{H2} of the jet increases with the L_{bol} of the source.

- Kinematic and dynamic data will be provided by forthcoming ISAAC/VLT observations at high spectral resolution.

In conclusion, our results indicate that the high-mass star forming process is a scaled-up version of the low-mass one.

References: Caratti o Garatti et al. 2006, A&A 449, 1077; Caratti o Garatti et al. 2008, A&A 485, 137; Cyganowski et al. 2008, AJ 136, 2391; Robitaille et al. 2007, ApJS 169, 328; Sánchez-Monge et al. 2013, A&A 552, L10; Stecklum et al. 2009, Protostellar Jets in Context, p619, Springer; Takami et al. 2012, ApJ 704, 8.