Proper motion analysis of HH212 and HH46/47

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ABSTRACT
Jets can facilitate the mass accretion onto the protostars in star formation. They are believed to be launched from accretion disks around the protostars by magnetocentrifugal force, as supported by the detections of rotation and magnetic fields in some of them. Here we report the physical motion analysis for two protostellar jets HH212 and HH46/47. Using multi-epoch imaging data, we measured the proper motions of jet features, calculated tangential velocities, and estimated dynamical ages of the observed knots. For HH 212, known for its symmetric and highly collimated structure, we measure jet velocities in the range of 70-200km/s increasing with distance from source star and jet acceleration of the order of $10^{-8} km/s^2$ and by measuring length of jet as 0.18pc , estimate age as ~1400 years. In contrast, HH 46/47 shows more complex and asymmetric features, with signs of episodic ejections and significant variability over time which are reflected in the wider velocity ranges of 50-350km/s. We also estimate age of ~700yr for the HH47A blow shock and verify our results against current literature.

Key words: ISM: individual objects (HH 212, HH 46/47) — ISM: Herbig-Haro objects — ISM: jets and outflows — stars: formation - stars: protostars

1 INTRODUCTION

Astrophysical jets from young stellar objects (YSOs) are narrow, high-speed outflows of ionized and molecular gas ejected along the rotational axes of forming stars. They play a crucial role in star formation by removing excess angular momentum and facilitating accretion onto the protostar. Jets can serve as a valuable source for studying early star formation dynamics. Typically extending up to a parsec, these jets are highly collimated and often exhibit bipolar structures. The formation of jets is not clearly understood; however, it is currently accepted that they are accelerated via a magnetohydrodynamical (MHD) process (Ferreira et al. (2006), Shang et al. (2007) and Pudritz et al. (2007)).
The HH 212 system is located in the Orion molecular cloud at a distance of approximately 400 parsecs and serves as an exemplary laboratory for studying protostellar jets. Driven by a deeply embedded Class 0 protostar, HH 212 exhibits a remarkably symmetric and collimated bipolar jet structure extending over parsec scales. Since the jet is almost in the plane of the sky, the jet velocity for HH212 can be approximated to its tangential velocity.
The HH 46/47 jet system (hereafter the HH 47 jet) is a bright and very complex HH jet emanating from a dense Bok globule in the Gum Nebula Schwartz (1977) that is powered by a binary star systemReipurth et al. (2000) . The whole system has several large bow shocks(HH47A, HH47C, HH47D) Eisloffel et al. (1994). HH47 A and HH47D towards the north/north east and HH47C towards the south.The total length from HH47C to HH47D is 0.57pc in projection at a distance of 450 pc.

1.1 Related works

Lee et al. (2022) performs radial velocity spectroscopy and measures the velocity of HH212 of the SiO jet over a distance of ~100-1000 AU and and reports a finding of 100-200km/s increasing with distance.It also shows that the jet has a higher mean velocity and a larger velocity range on the blue-shifted side than on the red-shifted side (see Figure 5, Lee et al. (2022)) probably due to different inclination angles of the jet in the northern and southern parts. Similarly Claussen et al. (1998) studied the velocity of the H_2O masers showing that they exhibit proper motions consistent with an association with an outflow jet accelerated to a velocity of 64 km/s within 40–70 AU of the central source. .Lee et al. (2015) estimates the proper motion of the jet to be ~115 ± 50 km/s using ALMA maps and Reipurth et al. (2019) indicates a velocity of about 170 km/sec that is highly symmetric around the source, with an uncertainty of ~30 km/sec and suggests a probable age of 7000 years for the system by doing a proper motion analysis using UKIRT images obtained through an H_2 filter with the time difference of 2882 days

Eisloeffel & Mundt (1994) gives a tangential velocities of about 100-300 km/s from source to HH47A. In other parts, tangential velocities are lower ~70-170km/s although these measurements are at a assumed distance of 350pc. Reipurth & Pettersson (1993) calculated a nearly constant velocity for HH46C of 111km/s but decelerating upto 50km/s for the downstream difuse component Schwartz & Greene (2003) finds the heliocentric velocity of HH46C as 31.6km/s and a heliocentric velocity of 105km/s for HH47A. Morse et al. (1994) reports a age of 1000 years with a large mass ejections occuring every 400yr or so. However, wide field images have revealed a large jet size and age of $10^4 - 10^5$ years Stanke et al. (1999)

In this study we aim to perform proper motion analysis for finding velocity, acceleration and thus calculating the age for HH212 and HH47 and comparing the physical properties of both jets. In terms of symmetry HH212 is famous for its remarkable symmetry whereas HH47 is assymetric. We expect this symmetry to show up in our velocity and acceleration measurements. We also expect to see more variations in velocity in HH47 due to the noted episodic ejections affecting acceleration

1.2 Organisation of report

In section 2 we present our methodology. In section 3 we presented our results, and in section 4 we discuss our findings and provide concluding remarks.

2 METHODS

2.1 Datasets

The HH212 protostellar system was observed for three epochs. Two epochs were obtained from the JWST data release in the Infrared waveband for the F212N filter on 27th November 2022 and 6th November 2023. The target was observed with a total time of 3607.56sec for both epochs. The third epoch was obtained from the Hubble Space Telescope data release in the same filter (F212N) on 9th March 2023 for a total exposure time of 4607.28 seconds. Observations of the HH47 system were obtained from the Hubble space telescope for two epochs. Both images were taken in the F673N filter on 26th March 1994 with an exposure time of 11900 seconds and on 31st December 2007 with an exposure time 7500 seconds.

2.2 SAOImageDS9

SAOImageDS9 is an astronomical imaging and data visualization application. DS9 supports FITS images and binary tables, multiple frame buffers, region manipulation, and many scale algorithms and colormaps.

2.3 Scale and contour analysis

For our analysis of the jets images we use DS9 to perform scale analysis,color mapping and contour analysis. We used log scaling with color mapping and manipulated scale parameters to obtain scaled colormapped images 1 which is then followed by contour analysis to estimate velocities. The scale parameters used for our analysis were the following:

- HH212 : -0.02 low and 5.45 high
- HH47 : -0.02 low and 0.1 high

Fig 1 shows that HH212 consists of a chain of knots and bow shocks with sinuous (continuous) structures in between. The northern lobe is predominantly blueshifted and the southern is redshifted. As for HH47, we see a very bright knot HH47A at its north eastern end. HH47D was very faint in the filters that we used and is thus not included as part of this analysis but would typically be further northeast from HH47A. Southwest of the source is the faint counterjet which is pointing towards HH47C. It is also notable that unlike HH212, HH47 does not show symmetry around the protostar and has relatively strong bends and kinks which can be attributed to the strong wiggling of the jet. In this jet system, HH47C is redshifted and HH47A is blueshifted.

SAOImage DS9 has the ability to create contours by overlaying lines on an image, representing areas of constant value. These contours are generated by adjusting parameters like the number of contour levels, smoothness, and the range of values to use. We uses 4 contours levals with the contour range same as the scale parameters range to maintain a good balance between required processing resources and gathering useful information from the images Fig 2 and 3 shows the results after doing contour analysis on HH212 by overlaying contours from an older epoch to the recent epoch which shows the extent of jet angular displacement.

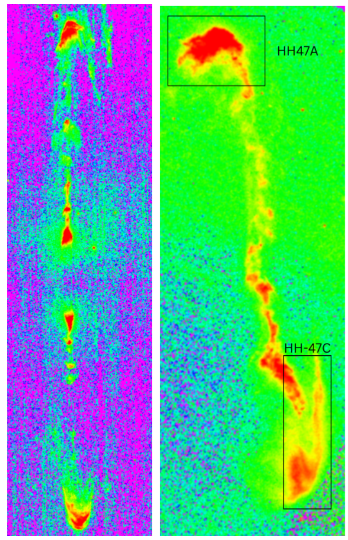

Figure 1. Left: HH212 from JWST as of 11/2023. Right: HH47 from HST as of 12/2007

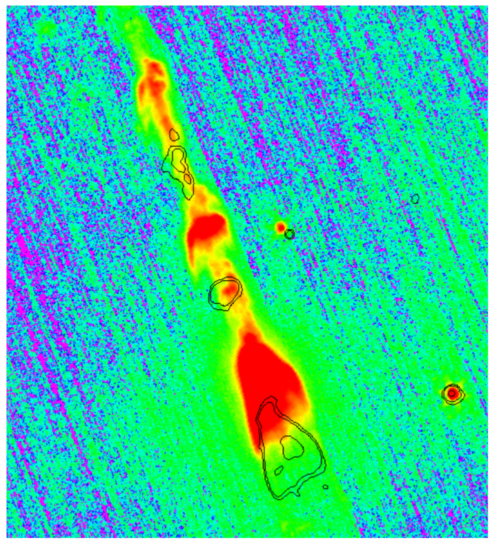

Figure 2. HH212 JWST with contours of HST epoch for a knot next to source star

2.4 Jet Kinematics

In the following sections, we discuss our methodology and results of velocity, acceleration and age analysis for HH212 and HH47

2.4.1 *Velocity analysis*

We recognise several knots(or working surfaces) in the jet flow and analyse the angular displacement of those knots for newer epochs with respect to the old one. 2 shows significant displacement for a blob in the blue shifted region right next to the source protostar. We consider each blob on the jet and measure the angular displacement using the

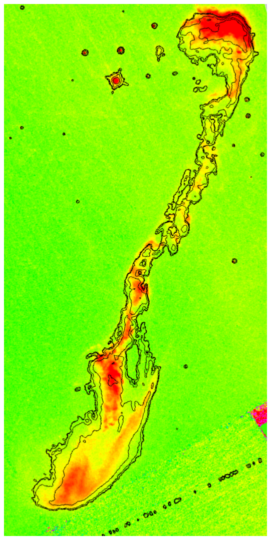

Figure 3. HH47 HST 2007 with contours of HST epoch 1994

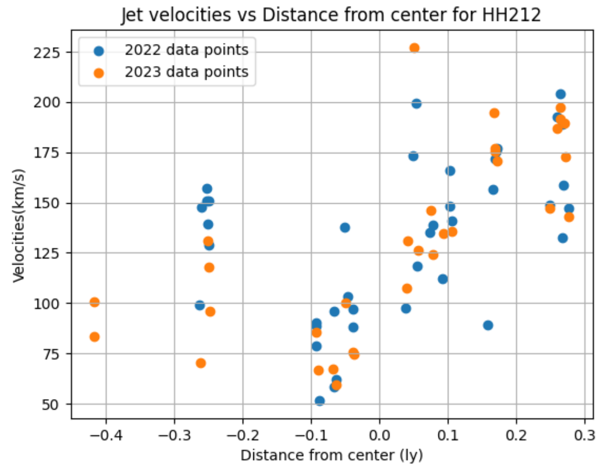

Figure 4. Measured velocities for jet HH212

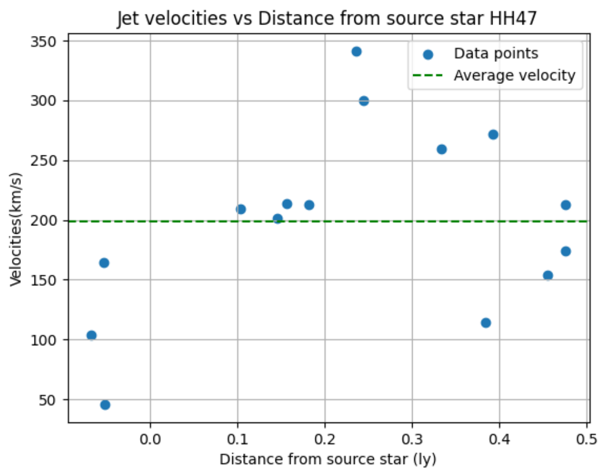

Figure 5. Measured velocities for jet HH47

contours. We perform this analysis twice for HH212 considering two epochs at a time and then compare the two individual results.

The projected linear distance travelled by a knot $d_{\rm blob}$ is calculated as:

$$d_{\rm blob} = \theta \times D \tag{1}$$

where:

- θ is the angular displacement of the jet feature between observations calculated by contours, measured in radians.
- D is the distance from Earth to the protostar in kms

With the projected distance determined, the velocity $v_{\rm blob}$ of the working surface is estimated by:

$$v_{\rm blob} = \frac{d_{\rm blob}}{\Delta t} \tag{2}$$

where:

- Δt is the time interval between the two observational epochs, in seconds.

We assume distance to jet as 400pc for HH212 (Lee et al. (2015), Lee et al. (2017), Reipurth et al. (2019)) and 450 pc for HH47(Hartigan et al. (2005), Reipurth & Heathcote (1991), Stanke et al. (1999)). We present the velocities for both the jets in 4 and 5

2.4.2 *Acceleration analysis*

Fig 4 shows the velocities of the jet as a function of the distance from the jet source protostar for HH212. It is notable that the jet velocities increase as the distance from the center increases. This signals towards the jet having some acceleration. This is explainable by considering the magneto-centrifugal model of acceleration for jets which can continue to accelerate the jet over extended distances. To estimate the acceleration of a working surface within a protostellar jet, we apply the kinematic equation:

$$v^2 = u^2 + 2as \tag{3}$$

where:

- v is the final velocity of the knot,
- u is the initial velocity (assumed to be the velocity of the knot closest to the protostar),
- a is the acceleration,
- s is the displacement between the initial and final positions of the knot. In our case this is equal to distance from center of source star

Rearranging the equation to solve for acceleration:

$$a = \frac{v^2 - u^2}{2s} \tag{4}$$

This approach assumes that the motion of the knot is primarily along the jet axis and that external influences (such as interactions with the ambient medium) are negligible over the measured segment.

2.4.3 *Age analysis*

To estimate the age of a protostellar jet, we apply the fundamental relation between distance, velocity, and time:

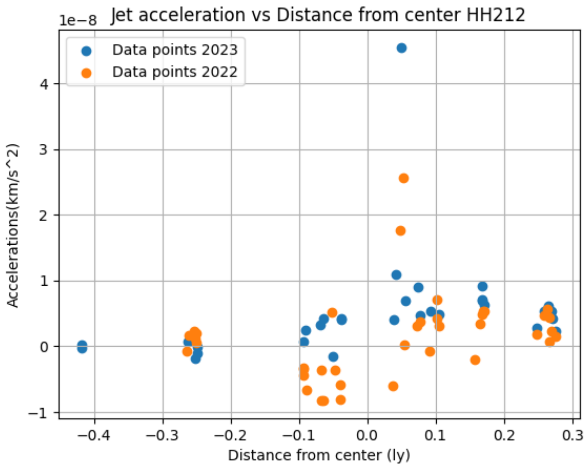

Figure 6. Measured accelerations for jet HH212

$$\text{Age} = \frac{\text{Jet Length}}{\text{Average Velocity}} \tag{5}$$

In this context:

- **Jet Length** is the projected linear distance from the central protostar to the furthest detectable emission along the jet axis.
- **Jet Velocity** is the effective jet velocity obtained by averaging over all measured velocities

We measure length of jet as 0.18pc for HH212 and 0.14pc for HH47 for the blue shifted mode and use average velocity values of 131.94 km/s for HH212 and 198.65 km/s for HH47 for age calculation.

3 RESULTS AND DISCUSSION

3.0.1 HH212

4 show the velocities measured over different knots on the jet systems. The plotted data shows velocities by two distinct observational epochs: one from 2022 and another from 2023. Both sets of measurements were compared against archival Hubble Space Telescope (HST) data from 1998. Velocities for both of these epochs are agreeable showing similar trends of velocity barring some noise.

Velocities obtained for HH212 show a very clear linear rise as distance from source increases. This trend is shown for both the redshifted and the blueshifted modes indicating general symmetry of the jet around the source star. The redshifted mode shows lower velocity values(shown in plots with negative distance) when compared to the blueshifted modes which is expected. The average velocity of jet obtained is 131.94 km/s which is consistent with velocity values reported by existing works 1.1

Following plot 6 shows the acceleration values for the jet knots. Plot for analysis with 2022 epochs shows range of acceleration to be around $0 - 10^{-8} km/s^2$. Analysis with epoch 2023 data shows very similar values except for the knot right next to the center in the red-shifted mode, which could signal possible deceleration.

Finally we measure an age of ∼ 1400 years for the jet assuming length from center to end of 0.18pc and jet velocity of 131.94km/s. This estimate is notably shorter than the ∼ 7,000-year age reported by Reipurth & Heathcote (1991)) The discrepancy likely arises because our analysis focuses on the inner segment of the jet, encompassing recently ejected knots. This interpretation aligns with findings by Lee et al. (2015) and Lee et al. (2007), who observed the inner 80¨ (∼ 0.16pc) of the HH212 jet exhibits distinct knots and bow shocks, indicative of recent ejection events. Therefore, our age estimate reflects the recent activity within the jet's inner regions rather than the total age of the entire HH212 outflow.

3.0.2 HH46/47

5 show the velocities measured over different knots on the jet systems. Unlike HH212 the range of velocities is larger with sharp kinks in the blue-shifted region with velocities around 300-350 km/sec. The source star of this jet is not in the center of the jet but is present closer to HH47C which can be observed by comparing the relative motion of the jet knots over two epochs. It is also worth noting that the counter jet HH46 and the working surface HH47C has been observed together as part of this analysis due to lack of measurement accuracy to be able to discern the two. There is a decrease in velocity for HH47C (marked as negative distance in the plot) with velocities around 150km/sec near the source star which decreases to 50km/sec near the apex. There were also only 3 observation points for this region since only the brighter northern parts of the flow could be seen.

Due to the higher variability of velocities, acceleration values for individual knots are likely to be powered by mechanisms other than the jet flow.

Finally on the basis of the average velocity of 198.65km/s and assuming a length of 0.14pc for the jet from source to apex of HH47A, we estimate an age of ∼708 years for the jet which is comparable with the reported age of ∼550 years for HH47A Morse et al. (1994)

4 CONCLUSION

We have performed proper motion analysis on the HH212 and HH46/47 herbig-haro objects to obtain jet velocities, acceleration and estimate the age of these jets. Our measurements confirmed the high-velocity outflows characteristic of both systems, with jet velocities consistent with previous studies.

- H212 jet velocities range from 70-200km/s with higher velocities visible in the blueshifted mode of the jet. In infrared band, jet can be observed as symmetric distribution of knots indicative of periodic ejections by the source star in the center. We measure mostly constant accelerations of order of magnitude $10^{-9} km/s^2$ with some outliers which can be possibly attributed to uncertainity in human measurement of angular displacement.
- HH46/47 is a much more complex jet than HH212. The source star is located towards the bow shock HH47C and jet shows evidence of periodic ejections. We estimate a velocity range of 100-350 km/sec with the velocties in apex of HH47A closer to 200km/sec and the bow shock HH47C to range from 100km/s to 50km/s closer to the apex
- Based on the measured velocties, we estimate an age of ∼1400 years for the inner knots of HH212 and ∼700 years for HH47A bow shock

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REFERENCES

Claussen M. J., Marvel K. B., Wootten A., Wilking B. A., 1998, The Astrophysical Journal, 507, L79

Eisloeffel J., Mundt R., 1994, Astronomy and Astrophysics (ISSN 0004-6361), vol. 284, no. 2, p. 530-544, 284, 530

Eisloffel J., Davis C. J., Ray T. P., Mundt R., 1994, Astrophysical Journal, Part 2-Letters (ISSN 0004-637X), vol. 422, no. 2, p. L91-L93, 422, L91

Ferreira J., Dougados C., Cabrit S., 2006, Astronomy & Astrophysics, 453, 785

Hartigan P., Heathcote S., Morse J. A., Reipurth B., Bally J., 2005, The Astronomical Journal, 130, 2197

Lee C.-F., Ho P. T., Hirano N., Beuther H., Bourke T. L., Shang H., Zhang Q., 2007, The Astrophysical Journal, 659, 499

Lee C.-F., Hirano N., Zhang Q., Shang H., Ho P. T., Mizuno Y., 2015, The Astrophysical Journal, 805, 186

Lee C.-F., Li Z.-Y., Ho P. T., Hirano N., Zhang Q., Shang H., 2017, The Astrophysical Journal, 843, 27

Lee C.-F., Li Z.-Y., Shang H., Hirano N., 2022, The Astrophysical Journal Letters, 927, L27

Morse J. A., Hartigan P., Heathcote S., Raymond J. C., Cecil G., 1994, Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 425, no. 2, p. 738-754, 425, 738

OpenAI 2025, ChatGPT (4o), https://chatgpt.com/

Pudritz R. E., Ouyed R., Fendt C., Brandenburg A., 2007, Protostars and planets V, 277

Reipurth B., Heathcote S., 1991, Astronomy and Astrophysics (ISSN 0004-6361), vol. 246, no. 2, June 1991, p. 511-534., 246, 511

Reipurth B., Pettersson B., 1993, Astronomy and Astrophysics (ISSN 0004-6361), vol. 267, no. 2, p. 439-446., 267, 439

Reipurth B., Yu K. C., Heathcote S., Bally J., Rodríguez L. F., 2000, The Astronomical Journal, 120, 1449

Reipurth B., Davis C., Bally J., Raga A., Bowler B., Geballe T., Aspin C., Chiang H.-F., 2019, The Astronomical Journal, 158, 107

Schwartz R. D., 1977, Astrophysical Journal, Lett., Vol. 212, p. L25-L26, 212, L25

Schwartz R. D., Greene T. P., 2003, The Astronomical Journal, 126, 339

Shang H., Li Z.-Y., Hirano N., 2007, Protostars and planets V, p. 261

Stanke T., McCaughrean M. J., Zinnecker H., 1999, arXiv preprint astro-ph/9909357

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