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NUMERICAL SIMULATIONS OF HH 211: A REFLECTION-SYMMETRIC BIPOLAR OUTFLOW

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ABSTRACT

Recent high-resolution, high-sensitivity observations of protostellar jets have shown many to possess an underlying 'wiggle' structure. HH 211 is one such example where recent sub-mm observations revealed a clear reflection-symmetric wiggle. An explanation for this is that the HH 211 jet source is moving as part of a protobinary system. Here we test this assumption by simulating HH 211 through 3D hydrodynamic simulations using the PLUTO code with a molecular chemistry and cooling module, and initial conditions based on an analytical model derived from SMA observations. Molecular chemistry allows us to accurately plot synthetic molecular emission maps and position-velocity diagrams for direct comparison to observations, enabling us to test the observational assumptions and put constraints on the physical parameters of HH 211. Our preliminary results show that the reflection-symmetric wiggle can be recreated through the assumption of a jet source being part of a binary system.

Key words: hydrodynamics – molecular processes – ISM: Herbig-Haro Objects – ISM: jets and outflows

1. INTRODUCTION

Protostellar jets and outflows are an essential constituent of the star formation process. They regulate the rotating collapse of a star forming cloud into a young star by removing excess angular momentum from the system. This occurs as the removal of a fraction of accretion material that is collimated and accelerated away at supersonic velocities from the central source in the form of bipolar jets. The jets in turn entrain and excite ambient cloud material forming the bipolar outflows. The shocked molecular gas produced by these bipolar outflows were traditionally observed as Herbig-Haro objects.

The precise mechanism behind how the jets are launched, collimated, and accelerated, to ultimately propagate up to tens of thousands of Astronomical Units (AU) is not yet fully understood, but by studying these large scale extended structures through a combination of observation, theory, and simulation, we can reveal more about the small scale launching region around the heavily obscured protostar.

Herbig-Haro object 211 (HH 211) is a relatively young ∼1,500 year old bipolar molecular outflow in the Perseus molecular cloud complex. It is ∼280 pc distant and covers ∼18,000 AU in the sky (Lee et al., 2009). Recent Submillimeter Array (SMA) observations of HH 211 by Lee et al. (2010) have revealed a clear underlying reflection-symmetric wiggle of the jet and counter-jet [See Fig. 5 of Lee et al. (2010)]. This can be explained by a translational motion of the jet source where the jet source is part of a protobinary system. This is in contrast to a point-symmetric wiggle where the jet system would be precessing (e.g. HH 34 is an example of a point-symmetric wiggle [See Reipurth et al. (2002)].

An analytical model fitting the observed reflection-symmetric wiggle of HH 211 was derived by Lee et al. (2010). Here we use this analytical model as the basis of 3D numerical simulations with molecular cooling and chemistry for creating synthetic molecular emission maps for direct comparison to observations.

2. NUMERICAL METHODS

The simulations are performed using the PLUTO (V4.1) astrophysical fluid dynamics code. It is a modern multi-physics, high-resolution, high-order shock-capturing Godunov code with a modular design (Mignone et al., 2007). We use a molecular cooling and chemistry module in the form of a full time-dependent non-equilibrium H_2 function which self-consistently tracks the destruction and formation of H_2, HI, and HII. We also employ CO rotational cooling, plus CO-H and CO-H_2 vibrational cooling from Smith & Rosen (2003), but at a fixed abundance ($n\mathrm{CO} = 10^{-5} n\mathrm{H}_2$). (See Table 1 and Fig. 1 of Moraghan et al. (2015 in preparation) for a detailed list of the chemical reactions and resultant cooling rates). The cooling functions operate in conjunction with an Equation of State that takes into account the degree of freedom arising from the rotational and vibrational modes of H_2.

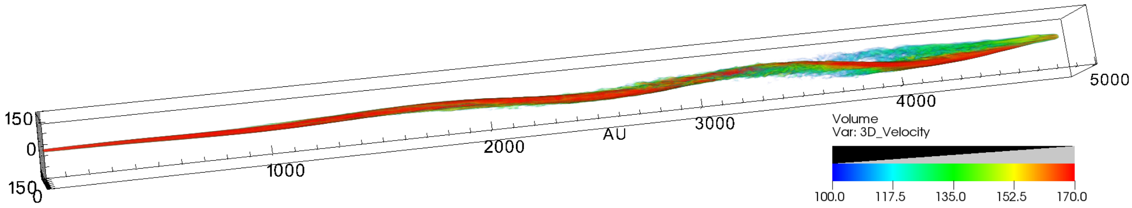

Figure 1. Volume rendering of the high velocity material of a constant velocity jet using our orbiting jet model. A constant velocity jet is presented here for illustrative purposes to highlight the wiggle motion of the jet beam.

Our jet model is based on the analytical description for the wiggle motion of HH 211 observed by the SMA from Lee et al. (2010). In this model the jet source is simply moving in a circle with an orbital radius of 2.3 AU and a period of ∼43 years (See Fig. 4 of Lee et al. (2010)). We assume the jet beam has already formed and collimated off the grid, so we introduce the collimated beam with a radius 20 AU and a velocity of 170 ± 20 km s^{-1} ensuring the correct amount of mass is introduced to the grid within the time frame of the simulation. The velocity pulsation is required to create the observed knotty structure.

Using column density maps of the HH 211 envelope from Very Large Array (VLA) observations by Tanner & Arce (2011), we estimate a suitable ambient density for our simulation. We set an initial ambient medium volume density of 10^6 cm^{-3} with a decreasing density profile at a uniform temperature of 10K. We set the jet beam volume density to 2.8×10^6 cm^{-3}, as estimated by Lee et al. (2010), and at a temperature of 100K. We consider both the ambient medium and jet beam composition to be fully molecular.

We simulate only one of the bipolar jets and mirror the results to obtain the counter jet for our data analysis. Therefore we set the dimensions of the 3D computational domain as $150\times150\times5000$ AU. The high-densities and low-temperatures means a high-rate of molecular cooling makes the simulation computationally intensive, therefore our current run is limited to a resolution of 10 zones per jet radius.

3. RESULTS

An example of one of our simulations is presented in Figure 1. This is a volume rendering of the high velocity jet material, effectively tracing the jet beam. We show a constant velocity jet here to highlight the wiggle structure caused by the orbiting motion. A more detailed model with a pulsing jet beam will be analysed in Moraghan et al. (2015 in preparation). Assuming a velocity variation creates the knotty structure as seen in the bright molecular emission knots observed in HH 211, we will use the locations where the knots trace the wiggle structure in an attempt to determine the points in the orbit of the source where the pulsing occurs. If a velocity pulse in the jet beam is a byproduct of an enhanced accretion event onto the source protostar, perhaps due to close passage to the binary companion or to the inner edge of the accretion disk, we can make assumptions and put physical constraints on the dynamics of the small scale heavily obscured protobinary system.

4. CONCLUSIONS

We perform 3D hydrodynamic simulations using the PLUTO code with a full time-dependent H_2 cooling and chemistry module, plus CO cooling at fixed abundance, allowing us to track the molecular species and plot synthetic molecular emission maps for direct comparison to SMA and ALMA observations. Specifically, we study the recently discovered reflection-symmetric structure of HH 211 using the analytical model from Lee et al. (2010). Our initial results show that the observed reflection-symmetric wiggle of HH 211 can indeed be accounted for by an orbiting jet source in a protobinary system, and molecular emission knots can be created by internal shocks caused by velocity variations of the jet beam. In the full publication, we will create synthetic molecular emission maps and position velocity diagrams for comparison with current and future observations to put further physical constraints on the HH 211 system.

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