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AN INTEPRETIVE BALLISTIC MODEL FOR QUASI-SYMMETRIC BIPOLAR JET SYSTEMS

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RESUMEN

Presentamos un modelo analítico, balístico para sistemas de chorros/contra-chorros cuasi-simétricos, considerando tanto el caso no relativista como el relativista. El modelo considera la presencia de asimetrías en el tiempo y en la velocidad de eyección, las cuales producen diferencias entre las posiciones de los nudos a lo largo del chorro y del contra-chorro. Un ajuste de las predicciones del modelo no relativista a observaciones de dos flujos HH cuasi-simétricos (HH 34 y HH 111) nos permite obtener las magnitudes de las asimetrías de tiempo y velocidad de eyección de estos sistemas.

ABSTRACT

We present an analytic, ballistic model for quasi-symmetric jet/counterjet systems, considering both the non-relativistic and the relativistic cases. The model considers the presence of ejection time and velocity asymmetries, which produce offsets between the positions of the knots in jet/counterjet pairs. A fit of the non-relativistic model predictions to observations of two quasi-symmetric HH outflows (HH 34 and HH 111) allows us to obtain the magnitudes of the ejection time and velocity asymmetries of these systems.

Key Words: Herbig-Haro objects — infrared: ISM — ISM: individual objects (HH 34, HH 111) — ISM: jets and outflows — stars: formation

1. INTRODUCTION

Many HH outflows do not have well defined symmetries between the red- and blue-shifted lobes. Examples of this are HH 32 (in which the red-shifted lobe is not well developed, see e.g., Curiel et al. 1997) and HH 262 (the outflow from the L1551 IRS5 source, which shows a very complex structure at all wavelengths, see e.g., López et al. 2008).

Other HH objects show at least some degree of similarity between the two outflow lobes. Gyul'budagyan (1984) presents a discussion of the partially symmetric bipolar structure of the HH 1/2 outflow. The deviations from perfect symmetry in bipolar HH outflows were discussed by Bally & Reipurth (2001) and Woitas et al. (2002), who studied the asymmetries in the ejection density and velocity between the two outflow lobes.

Some IR bipolar outflows from young stellar objects (YSOs) show a surprising degree of "knot by knot" symmetry between the two outflow lobes. Examples of this are HH 212 (see, e.g., Smith, O'Connell, & Davis 2007; Cabrit et al. 2007) and HH 211 (e.g., Lee et al. 2010). In the well studied HH 34 and HH 111 optical outflows, it has been noted that good jet/counterjet knot symmetries are also present, particularly when one combines optical with IR observations (in which the highly obscured counterjets are detected). This was seen in HH 111 by Gredel & Reipurth (1994) and in HH 34 by García López et al. (2008).

Recent IR images obtained with the IRAC camera of *Spitzer* of HH 34 (Raga et al. 2011) and HH 111 (Noriega-Crespo et al. 2011) give us the possibility of directly measuring the positions of the knots (relative to the source) along the jet and counterjet in a single image, and to carry out a quantitative analysis of the degree of symmetry in the

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