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EVIDENCE FOR PAST KNOT MERGERS IN THE HH34 JET

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RESUMEN

Dentro de ≈30″ de la fuente, el jet de HH34 tiene una cadena de nudos bien alineados. Las posiciones y los movimientos propios de estos nudos pueden ser usados para determinar tiempos dinámicos, y para estimar el período de eyección (tomando diferencias entre los tiempos dinámicos de nudos sucesivos). De esta manera, encontramos mayores períodos estimados para los nudos a mayores distancias de la fuente (o sea, a mayores tiempos dinámicos). Interpretamos este resultado con un modelo en que los nudos tienen una variabilidad azarosa de baja amplitud (≈15–20%) en su velocidad de eyección y un período bien definido de ≈16 años, lo cual lleva a la producción de algunos eventos de fusión de nudos.

ABSTRACT

Within ≈30″ from the outflow source, the HH34 jet has a chain of well aligned knots. The positions and proper motions of these knots can be used to determine dynamical timescales, and estimates of the ejection period (by taking differences between the dynamical timescales of the successive knots). Through this exercise, we find that larger estimated ejection periods are found for the knots further away from the outflow source (i.e., for the knots with larger dynamical timescales). We interpret this result in terms of a model in which the knots have a low amplitude (≈15–20%) random ejection velocity variability and a well defined period of ≈16 yr, leading to a few knot-merging events.

Key Words: Herbig-Haro objects — ISM: kinematics and dynamics — stars: formation

1. INTRODUCTION

HH34 was one of the first Herbig-Haro (HH) objects in which jet-like chains of aligned knots were observed (Reipurth et al. 1986). The proper motions observed for these knots (Reipurth 1989; Heathcote & Reipurth 1992; Eislöffel & Mundt 1992) were interpreted in terms of a variable ejection velocity jet model by Raga et al. (1990). This interpretation has been given strength by more recent observations showing an impressive jet/counterjet symmetry in HH34 (García López et al. 2008; Raga et al. 2011b) and by numerical simulations which reproduce some of the observed features of this object (e.g., Raga et al. 2011a). However, it has still not been explored whether or not variable outflow models (or for that matter, other types of jet models) can reproduce many of the extensive observations of the HH34 jet that have been made (see, e.g., Rodríguez-González et al. 2012).

Hartigan et al. (2011) obtained new HST images of HH34, providing a more extended time-line for calculations of proper motions (resulting in a substantial improvement on the previous HST proper motions of Reipurth et al. 2002). The resulting improved proper motions (Raga et al. 2012a) allow new studies of the kinematics of the knots along the HH34 jet. In this paper, we present an attempt to explore whether or not the observed kinematics of the HH34 jet shows evidence of past mergers between ejected knots.

The study of knot merging events dates back to Roberts (1986), who modeled the knot structures observed in extragalactic jets as the result of a hierarchy of mergers of smaller scale structures. Self-similar solutions giving the resulting knot separation vs. distance from the source scalings were explored by Raga (1992), who concluded that knots along

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(stellar or extragalactic) astrophysical jets are not present in large enough number for them to be in such a "knot collision dominated" regime. More recently, numerical simulations of HH jets ejected with random variabilities have been presented by Yirak et al. (2009) and Bonito et al. (2010a,b).

Using archival HST images of the HH34 jet covering a ≈9 yr time span, Raga et al. (2012a) determined improved proper motions for the knots along the HH34 jet. Extrapolating these motions into the future (assuming that they are ballistic), they find that a few "knot merging events" will occur over ≈500 yr, and that a large number of knot mergers will occur ≈900 yr in the future. Through a "momentum conserving knot model" and with axisymmetric numerical simulations, Raga et al. (2012b) showed that this major knot merging event will result in the creation of a large working surface resembling the present day HH34S.

Raga et al. (2012b) reconstructed the time-variable velocity ejection history by projecting the observed proper motion velocity vs. projected distance of HH34 onto an "ejection velocity vs. dynamical timescale" plane. They then used this reconstructed variability to reproduce the observed structure (and predict future structures) of HH34, adding an aditional ejection velocity variability mode in order to produce the aligned knot chain at the base of the HH34 jet.

In the present paper, we explore the following question: does the observed chain of knots within ≈30″ from the source of HH34 show evidence for past knot merging events?

Answering this question is not trivial, because after a knot merging event the memory of the fact that the merged knot is the result of the previous existence of two (or more) knots is partially lost. However, knot mergers result in a "disappearance" of knots at increasing distances from the outflow source.

Observing the proper motions and distances of the knots along a jet, one can determine the dynamical timescales of the successive knots, and the ejection period can be estimated by taking differences between these times. The presence of knot merging events will then be seen as an increase in the estimated ejection period for increasing dynamical timescales.

We derive the dynamical time and the estimated ejection periods (as differences between the dynamical times of the successive knots) for the HH34 jet knots in § 2, and present a wavelet spectrum of the resulting ejection period distribution. In § 3, we present a simple model of ballistic knots with momentum conserving mergers, with which we model the estimated ejection period vs. dynamical time of HH34. Finally, the results are summarized in § 4.

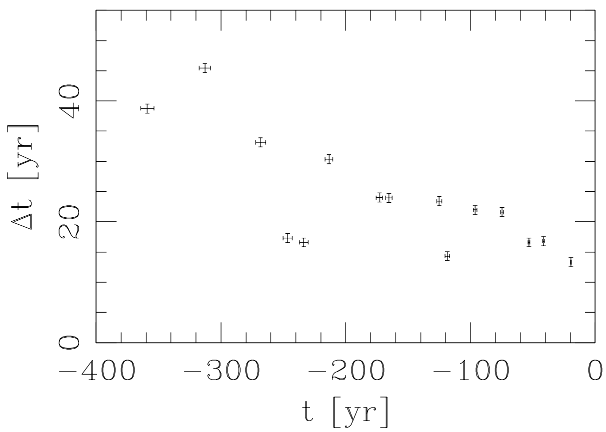

Fig. 1. Estimated ejection period Δt as a function of dynamical time t (see equations 1–2) for the knots along the HH34 jet. The error bars show the estimated observational errors.

2. EJECTION PERIOD VS. DYNAMICAL TIMESCALE

2.1. *General trend*

From the knot positions x_n and proper motion velocities v_n of Raga et al. (2012a, their Table 1) for 18 consecutive knots along the HH34 jet, we can calculate their dynamical timescales:

$$t_n = -\frac{x_n}{v_n}\,, \tag{1}$$

where $t = 0$ is the present time, and negative dynamical times are in the past.

We can then take differences between successive dynamical times in order to estimate the ejection period at the times at which the successive knots were ejected. For the estimate of the ejection period Δt_n at the time at which the n-th knot was ejected we use the centered difference:

$$\Delta t_n = \frac{1}{2}\left(t_{n+1} - t_{n-1}\right)\,. \tag{2}$$

From the 18 observed knots (see Table 1 of Raga et al. 2012a), with equations (1–2) we can obtain 16 $(t_n, \Delta t_n)$ points. Actually, we have eliminated knot 7, as this knot has a measured proper motion which is not consistent with a free streaming flow (see the discussion in § 4.2 of Raga et al. 2012a), and therefore we obtain only 15 $(t_n, \Delta t_n)$ points.

The resulting Δt vs. t relation is plotted in Figure 1. In this plot we see that the ejection periods estimated for the successive knots have a minimum value $\Delta t_0 = 16 \pm 2$ yr. The three knots with $|t| < 60$ yr, as well as three other knots at larger (in absolute value) times have estimated periods close to Δt_0.

A second group is composed by 5 knots with periods $\Delta t \approx 22 \to 25$ yr $\approx 1.5\,\Delta t_0$, which have dynamical times $-190 < t < -70$ yr. Finally, there is a third group with larger periods $\Delta t = 30 \to 47$ yr ($\approx 1.8 \to 2.9\,\Delta t_0$), all of them ejected more than 200 yr ago.

The Δt vs. t relation obtained from the knots along the HH34 jet (Figure 1) can be qualitatively described as follows. There is minimum value $\Delta t_0 \approx$ 16 yr for the ejection period, which is found for the most recently ejected knots, as well as for a few knots ejected at longer times in the past. The remaining knots have larger estimated ejection periods Δt, with the larger periods corresponding to the longer ejection timescales.

2.2. *Wavelet analysis*

In this section we present a wavelet analysis of the ejection period distribution. An early astronomical application of wavelet analysis was made by Gill & Henriksen (1990), and since then the use of wavelet analysis has become increasingly popular in astronomy (a good introduction to this topic is given in the book of Mohlenkamp & Pereyra 2008).

In order to illustrate the properties of the ejection period distribution described in § 2.1, we have taken the obtained distribution and convolved it with a basis of "French hat" wavelets

$$
\begin{aligned}
f_a(x) &= \frac{1}{a}\,; & |x| \le a\,, \\
&= -\frac{1}{2a}\,; & a < |x| \le 2a\,, \\
&= 0\,; & |x| > 2a\,,
\end{aligned}
\tag{3}
$$

with $a = 1, 2, \ldots 15$ yr. The resulting wavelet spectrum of the ejection period distribution is shown in Figure 2.

The wavelet spectrum is given in an a vs. Δt plane (where Δt is the estimated ejection period, and a is the half-width of the wavelets, see equation 3). The spectrum has two strong peaks at $\Delta t \approx 16$ and 23 yr, both with an $a = 2$ ordinate (see Figure 2). These two groups of ejection periods correspond to the $\Delta t \approx \Delta t_0$ and $\approx 1.5\ \Delta t_0$ groups described in § 2.1. The fact that both groups show peaks with $a = 2$ yr indicates that this is the value of the half-widths of the ejection period distributions of the two groups.

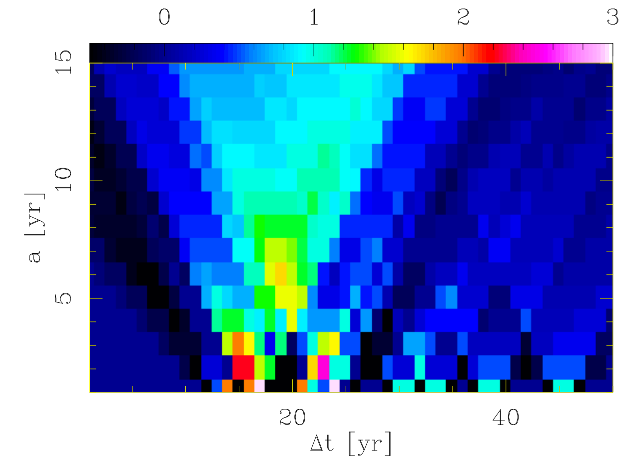

Fig. 2. Wavelet spectrum of the ejection period distribution obtained for the HH34 jet knots. The bottom row of pixels represents the Δt distribution convolved with an $a = 1$ wavelet (see equation 3), and the successive rows at higher values of the ordinate are the convolutions with broader wavelets. It is clear that two principal components (with periods of $\approx$16 and $\approx$23 yr) are found. These two components are quite narrow, as evidenced from the fact that they are brightest at low a values. The color figure can be viewed online.

A third peak in the wavelet spectrum is found at $a = 6$, $\Delta t = 19$ yr (see Figure 2). This peak represents the fusion of the $\Delta t \approx \Delta t_0$ and $\approx 1.5\ \Delta t_0$ groups into a single, broader group at larger widths of the wavelets.

Finally, we find a number of peaks with $\Delta t = 30 \to 50$ yr at $a = 1$ (see Figure 2). These peaks correspond to the knots with larger estimated periods found at the more negative ejection timescales (see Figure 1), which have Δt values with a relatively large scatter.

This wavelet analysis therefore shows evidence that the ejection periods deduced from the knots along the HH34 jet clearly fall within two narrow groups, with mean ejection periods of $\approx$16 and 23 yr and widths of ± 2 yr. The fact that no knots with ejection periods $\Delta t < \Delta t_0 = 16$ yr are found appears to be a real effect, because this ejection period (together with a knot velocity of $\approx$150 km s^{-1} and a distance of $\approx$414 pc, see Raga et al. 2012a) corresponds to an angular separation of $\approx 1''.3$, so that if knots with considerably closer spacings were present, they should be clearly separated at the $\approx 0''.1$ resolution of the HST images. This minimum value of the ejection period is therefore likely to correspond to a real physical property of the HH34 jet.

Finally, we have tried to quantify whether or not the two main peaks of the ejection period distribution (at $t = 16$ and 23 yr, with full widths of ≈4 yr, see above) correspond to significant deviations from a random distribution. To this effect, have carried out 10^6 simulations in each of which we randomly choose 16 periods between 0 and 50 years. We find that in a fraction $f = 0.0069$ of these simulations, we have 5 or more periods falling within an abritrarily centered, 4 yr wide band. Therefore, the $t = 16$ and 23 yr peaks in the observed ejection period distribution (each of them having ≈5 periods within bands with a ≈4 yr width) represent deviations from a random period distribution with a significance of $1 - f \approx 99.3\%$.

3. BALLISTIC, MOMENTUM CONSERVING KNOT MODEL

3.1. *General considerations*

In order to try to reproduce the Δt vs. t trend observed for the knots along the HH34 jet (see Figure 1), we use a momentum conserving, ballistic knot model. It would be clearly possible to reproduce a monotonically increasing Δt vs. t relationship with an ejection velocity law which has a period that decreases with increasing time (i.e., with lower Δt values for the more recently ejected knots). However, such a simple ejection velocity history seems to be ruled out by the fact that the minimum estimated ejection period ($\Delta t_0 \approx 16$ yr, see § 2) is not only found for the more recently ejected knots, but is also present in some of the more distant knots (ejected at more negative dynamical times).

This observed Δt vs. t relation, with a minimum ejection period but with a general trend of larger Δt for more negative t favors a model in which the knots are ejected with a constant period Δt_0 and with a variable ejection velocity. The differences in the ejection velocities of the successive knots then lead to knot mergers which produce the observed growth of Δt for more negative ejection times.

3.2. *The first knot merger*

We now consider a model in which the knots are ejected with a steady period Δt_0 (which would correspond to the minimum period obtained from the knots along the HH34 jet, see § 2), and a variable velocity. The increase in estimated ejection periods at more negative dynamical timescales (see Figure 1) would then correspond to the loss of knots resulting from mergers between successive ejections.

We assume that the ejection velocity has a random, uniform distribution with a mean velocity v_0 and a half-width Δv. Then, two successive ejections will have velocities v_1 and v_2 with a mean square velocity deviation

$$\sigma_v^2 =< (v_2 - v_1)^2 >=$$
$$= \int_{v_0-\Delta v}^{v_0+\Delta v} \left[\int_{v_0-\Delta v}^{v_0+\Delta v} (v_2 - v_1)^2 f(v_1) f(v_2) dv_1 \right] dv_2 \, , \tag{4}$$

which for the simple, $f(v) = 1/(2\Delta v)$ form of the uniform distribution can be integrated to obtain:

$$\sigma_v = \sqrt{\frac{2}{3}} \Delta v \, . \tag{5}$$

Let us now consider two successive ballistic knots, the first one ejected with a velocity $v_0 - \sigma_v/2$ and the second one ejected (after a time Δt) with a velocity $v_0 + \sigma_v/2$. These two knots will merge after a time

$$t_m = v_0 \Delta t / \sigma_v \, . \tag{6}$$

During the time t_m to this knot merging event, a total number

$$N_m = \frac{t_m}{\Delta t} \tag{7}$$

of knots are ejected. Therefore, if we know which is the number of knots N_m including the first merged knot, we can combine equations (5–7) to calculate the fractional width

$$\frac{\Delta v}{v_0} = \sqrt{\frac{3}{2}} \frac{1}{N_m} \, . \tag{8}$$

From Figure 1, we see that the 4th knot (starting from $t = 0$) has a larger estimated Δt, so that it would correspond to the first merged knot. Therefore, we have $N_m = 4$, which (through equation 8) gives $\Delta v / v_0 \approx 0.3$.

This evaluation of the amplitude of the random velocity variability of the successive ejections is, of course, only an order of magnitude estimate, since it is based on the assumption that the first merger is produced by two knots with the mean square velocity deviation (equation 5) obtained from the assumed distribution. Clearly, the observed first merger could correspond to a pair of knots with a velocity difference which deviates substantially from σ_v.

3.3. *Colliding knots simulation*

We now compute models of aligned ballistic knots which are ejected with a fixed period $\Delta t = 16$ yr, and with a uniform velocity distribution with a mean

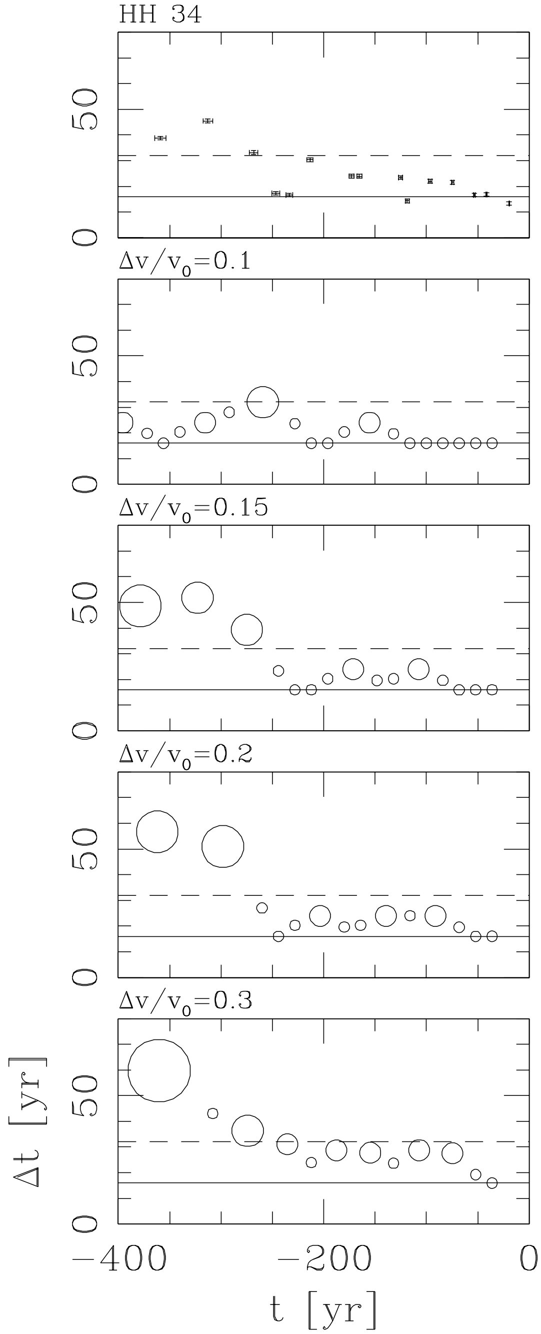

Fig. 3. Estimated period Δt vs. dynamical timescale t (see equations 1–2) obtained for the HH34 jet (top) and for ballistic, momentum conserving knot models with an ejection period of 16 yr and random ejection velocities with $\Delta v/v_0 = 0.1$, 0.15, 0.2 and 0.3 (see the text). The horizontal lines indicate a period $\Delta t_0 = 16$ yr, and the dashed lines a period of $2\Delta t_0$. The $(t, \Delta t)$ points predicted from the models are depicted with open circles with radii proportional to the masses of the (possibly merged) knots.

velocity $v_0 = 150$ km s^{-1} (similar to the proper motions of the knots along HH34, see Raga et al. 2012a) and different half-amplitudes Δv. The knots are ejected with identical masses m. When "catching up" events occur, the knots are assumed to merge, forming a "combined knot" with the mass and momentum of the colliders (see Raga et al. 2012b).

We compute models with $\Delta v/v_0 = 0.1$, 0.15, 0.2 and 0.3, and integrate the equations of motion for 500 yr. From the knot distributions resulting from these time integrations, we compute the "estimated ejection period vs. dynamical timescale" relation (see equations 1–2). The results of this exercise (together with the Δt vs. t relation obtained for HH34) are shown in Figure 3.

The $(t, \Delta t)$ points for the knots obtained in the models are shown with open circles with radii which are proportional to the knot masses. For example, for the $\Delta v/v_0 = 0.2$ model (see Figure 3), we have knots with the mass m of the ejected knots, and with merged masses of $2m$ and $4m$.

From Figure 3, we see that the models with $\Delta v/v_0 = 0.15$, 0.20 show Δt vs. t distributions which are qualitatively similar to the one found for the HH34 jet. The model with $\Delta v/v_0 = 0.10$ differs qualitatively from HH34 since:

- it has a clearly larger number of knots (7 instead of 4) until the first knot with a clearly increased estimated Δt is reached,
- it has no knots with $\Delta t > 2\Delta t_0$.

The $\Delta v/v_0 = 0.30$ model also differs from HH34, because it has a single knot with estimated $\Delta t = \Delta t_0$ (while HH34 has 3 such knots at recent dyamical timescales, and 3 more at more negative timescales).

In this way, we would conclude that models with random velocity variabilites with half-amplitudes in the $\Delta v/v_0 = 0.15 \rightarrow 0.20$ range reproduce the qualitative features of the HH34 jet's Δt vs. t dependence. This result is also obtained if we consider the wavelet spectra of the HH34 jet and of the $\Delta v/v_0 = 0.10$, 0.15, 0.20 and 0.30 models. These spectra are shown in Figure 4, where we see that for $\Delta v/v_0 = 0.15$ and 0.20 a good qualitative agreement with the observed wavelet spectrum is obtained.

4. CONCLUSIONS

From the proper motions of the knots along the HH34 jet of Raga et al. (2012a) we have obtained the dynamical times t and the estimated ejection periods Δt (obtained as differences between the dynamical times of the successive knots). The resulting Δt

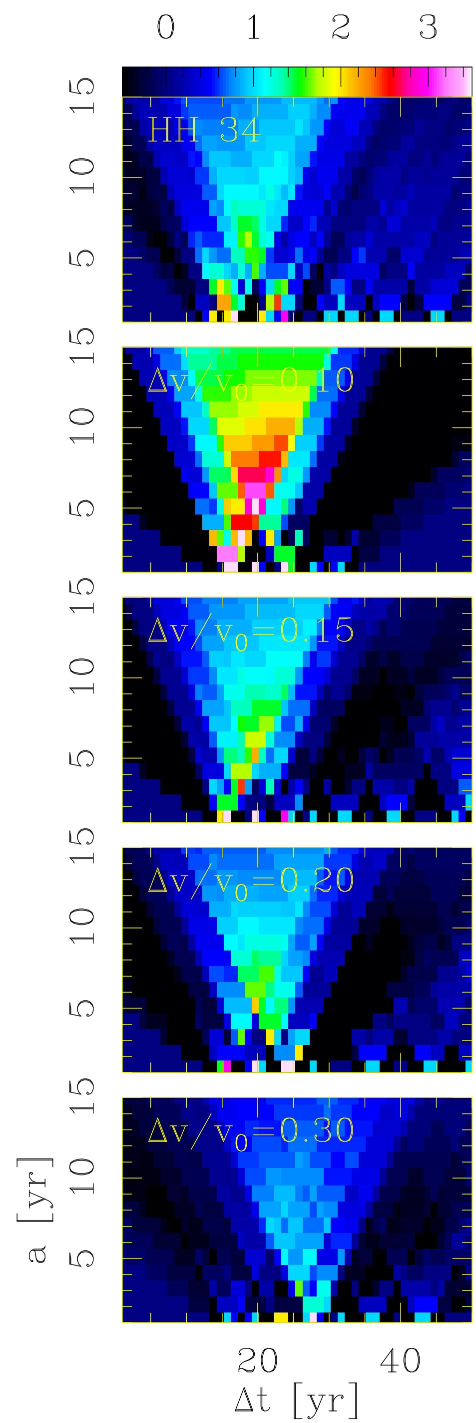

Fig. 4. Wavelet spectra of the estimated ejection period Δt distributions of the HH34 jet (top), and of the distributions predicted from ballistic, momentum conserving knot models with ejection velocity distributions with $\Delta v/v_0 = 0.1$, 0.15, 0.2 and 0.3. It is clearly seen that the $\Delta v/v_0 = 0.15$ and 0.2 models produce spectra which qualitatively resemble the observed wavelet spectrum. The color figure can be viewed online.

vs. t dependence (see Figure 1) has the following characteristics:

- the knots along the jet have a minimum estimated period $\Delta t_0 \approx 16$ yr,
- values of $\Delta t \approx \Delta t_0$ are found for the three most recently ejected knots (ejected in the past 60 yr), and for 3 other knots ejected up to 260 yr ago,
- a few knots with larger estimated ejection periods are found at the larger (i.e., more negative) dynamical timescales.

The fact that the minimum estimated period Δt_0 is found for some of the knots ejected at relatively long times eliminates the possibility of having a time variability with a monotonically increasing ejection period as a function of time into the past. We therefore explored the possibility of having a variability with a well defined ejection period $\approx\Delta t_0$ and with a randomly varying ejection velocity (for which we chose a uniform distribution with a mean velocity v_0 and a half-amplitude Δv).

Through an analytic argument about the formation of the first merged knot, we obtain an estimate $\Delta v/v_0 \approx 0.3$ for the random ejection velocity variability. Through a series of numerical experiments with a momentum conserving, ballistic knot model, we find that the motions of the HH34 knots can be best reproduced with an ejection velocity distribution with $\Delta v/v_0 \approx 0.15 \rightarrow 0.2$. This result is found from a direct comparison of the predicted and observed Δt vs. t relations (Figure 3) as well as through a wavelet analysis of the period distribution (Figure 4).

Some of the knots produced in the $\Delta v/v_0 = 0.15$ and 0.2 models are the results of mergers of 2 to 4 of the originally ejected knots. We would therefore expect the knots towards the end of the aligned knot chain of HH34 to be the result of a few previous knot merging events.

We end by noting that Raga et al. (2011c) analyzed the jet/counterjet knot-to-knot asymmetries of the HH34 outflow in terms of a ballistic knot model. They concluded that the jet/counterjet knot ejections are well coordinated (within the observational errors), but that they have ejection velocity asymmetries of $\approx$10 km s^{-1}. In the present study, we find that the observed proper motions and positions along the HH34 jet imply a well defined ejection period, and a small amplitude (possibly random) variability in the ejection velocity. These two possibly related effects might give insights into the mechanism which produces the ejection variability that gives rise to the structures observed along the HH34 outflow.

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