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DISCOVERY OF MICROSECOND TIME LAGS IN KILOHERTZ QPOs

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ABSTRACT

Using the *Rossi X-Ray Timing Explorer*, we have measured ∼27 μs time delays in 830 Hz quasi-periodic oscillations (QPOs) between 4–6 and 11–17 keV in 4U 1608−52, with high-energy photons lagging low-energy photons, and found upper limits to the time delays of 45 μs between 2–6.5 and 6.5–67 keV in ∼730 Hz QPOs in 4U 0614+091 and 30 μs between 8.7–12.4 and 12.4–67 keV in ∼870 Hz QPOs in 4U 1636−53. We also find that the cross-coherence function between QPOs at different energies is greater than 0.85 with 95% confidence in 4U 1608−52 and 4U 1636−53. If Compton upscattering of low-energy X-rays in a region with an optical depth of a few is responsible for the delays, then the Compton upscattering region is between a few kilometers and a few tens of kilometers in size.

Subject headings: accretion, accretion disks — stars: individual (4U 1608−52, 4U 0614+614, 4U 1636−53) — stars: neutron — X-rays: stars

1. INTRODUCTION

Quasi-periodic oscillations (QPOs) with frequencies $\nu_{\rm QPO} \sim$ 350–1170 Hz have recently been observed in power spectra of count-rate modulations in ∼10 X-ray binaries. These QPOs have fractional rms amplitudes of 1%–20% and quality factors $Q \equiv \nu_{\rm QPO}/\Delta\nu_{\rm QPO} = 10$–200, where $\Delta\nu_{\rm QPO}$ is the full width at half-maximum of the QPO peak in the power spectrum. In six sources, a pair of QPO peaks have been observed simultaneously (4U 0614+091, 4U 1728−34, Sco X-1, GX 5−1, 4U 1820−30, and 4U 1636−53), with frequencies separated by 200–400 Hz. In 4U 0614+091 and 4U 1728−34, the frequency separation remains constant during excursions in QPO frequency by ∼200 Hz. QPO frequency is strongly correlated with count rate in 4U 1820−30, 4U 0614+091, and 4U 1728−34, and with $\dot{M}$ as inferred from the Z track in GX 5−1 and Sco X-1 (van der Klis et al. 1996). A 363 Hz oscillation seen during X-ray bursts in 4U 1728−34 (Strohmayer, Lee, & Jahoda 1996a; Strohmayer et al. 1996b) has a frequency consistent with the difference between the pair of QPO peaks.

The frequencies of these QPOs may correspond to the Keplerian frequency, $\nu_{\rm Kep}$, at the inner edge of the Keplerian flow, which may be terminated by radiation forces, general relativistic corrections to Newtonian gravity, or perhaps the magnetic field of the neutron star, and to the difference, or beat, frequency between $\nu_{\rm Kep}$ and the spin frequency of the neutron star (Alpar & Shaham 1985; Lamb et al. 1985; Miller, Lamb, & Psaltis 1997). The oscillations seen in 4U 1728−34 during some bursts, which have a frequency equal to the difference between the frequencies of the two higher frequency QPOs, suggest this interpretation. The changing difference between the frequencies of the high-frequency QPOs seen in Sco X-1 (van der Klis et al. 1996) would then require the spin frequency to beat with a varying Keplerian frequency that is slightly different from the frequency of the higher frequency QPO in this source.

In the Z sources GX 5−1 and Cyg X-2, count-rate modulations at energies above ∼5 keV lag those below ∼5 keV by 1–10 ms in 15–55 Hz horizontal-branch QPOs (van der Klis et al. 1987; Vaughan et al. 1994), with the delay increasing with photon energy, and by 70 ms in 6 Hz normal-branch QPOs (Mitsuda & Dotani 1989; Vaughan et al. 1997; Dieters et al. 1997). In both cases, the cross coherence between oscillations at different energies is ∼1, meaning that they can be related to one another by a constant linear transformation (see Vaughan & Nowak 1997 for an explanation of the cross-coherence function, also called the coherence function, or simply coherence). No lags have so far been detected in normal-branch QPOs in Sco X-1 (Dieters et al. 1997). In the case of horizontal-branch oscillations, Compton upscattering of low-

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TABLE 1

OBSERVATIONS AND QPO PROPERTIES

System	Observation Date	Duration[a] (s)	Rate[b] (s^{-1})	ν_{QPO} (Hz)	rms[c]	Range[d] (Hz)
4U 1608−52	1996 Mar 3	3694	3100	830	0.07	820–840
4U 0614+091.....	1996 Mar 16	4918	560	730	0.13	680–780
4U 1636−53	1996 May 29	2360	1700	870[e]	0.07	862–877

[a] Length of data set used for analysis. Determined principally by the stability of the QPO frequency.
[b] Average count rate of data used in the analysis.
[c] Fractional rms amplitude of the QPO. Increases with energy in all sources.
[d] Range of frequencies used for analysis. Dictated by the QPO width and stability of the QPO centroid frequency.
[e] Average ν_{QPO} for the first 2360 s of the observation.

energy photons has been suggested as one possible explanation for the lags (Wijers, van Paradijs, & Lewin 1987; Stollman et al. 1987; Bussard et al. 1988), although differences in the lag at the QPO fundamental frequency and its harmonic in GX 5−1 challenge this interpretation (Vaughan et al. 1994). It is also possible to interpret the lags in the context of shot-noise models by postulating that individual shots "harden," i.e., become hotter, as they progress. Hardening shots can be used to produce any time delay, but Vaughan & Nowak (1997) point out that, for blackbody emission, hardening shots only result in unity cross coherence if the photons are emitted in the Rayleigh-Jeans part of the energy spectrum, in which case they lead to no delay. We report in this Letter the discovery of ∼27 μs hard lags in kilohertz QPOs and show that they are consistent with Compton upscattering in a region between a few kilometers and a few tens of kilometers in size, i.e., comparable to the size of a neutron star.

2. OBSERVATIONS

We have investigated time delays in the QPOs between different energy channels in 4U 1608−52, 4U 0614+091, and 4U 1636−53. These sources were chosen because each showed QPOs with high fractional rms amplitude, a moderate to high count rate, a narrow peak, and a stable frequency during at least one extended interval. We also, of course, required spectrally resolved data of sufficient time resolution.

All observations were performed using the proportional counter array on the *Rossi X-Ray Timing Explorer* (Bradt, Rothschild, & Swank 1993). Observation times and durations, and count rates, are given in Table 1, along with QPO properties (all of which were measured by previous investigators). Details of the QPOs in these sources can be found in Berger et al. (1996; 4U 1608−52), Méndez et al. (1997; 4U 0614+091), and Wijnands et al. (1997; 4U 1636−53). A single QPO peak was present in each observation. We were unable to investigate time lags in observations containing two QPO peaks because data with sufficient signal strength were unavailable (see § 3). We calculated the cross spectra in the manner described by Vaughan et al. (1994).

Instrumental dead time can cause a bias in measurements of time delays, by introducing an anticorrelation between pairs of energy channels that manifests itself as a 180° phase difference in the cross spectrum between pairs of energy channels at all frequencies. Because the count rates for each of the sources investigated here were small compared with the inverse of the instrumental dead time, the fractional dead time was typically less than 1%, and dead time had a completely negligible effect on cross spectra measured at the QPO frequency.

3. RESULTS

Measurement of time delays and the cross-coherence function in the presence of a counting-noise background is discussed in detail by Vaughan et al. (1994) and Vaughan & Nowak (1997). The crucial quantity for determining whether a meaningful estimate of the time delay between two light curves is possible is the signal-to-noise ratio, given by $S/N = f_1 f_2 r_1^{1/2} r_2^{1/2} T^{1/2} \Delta\nu^{-1/2}$, where f_1 and f_2 are the fractional rms amplitudes of the QPOs in the two light curves, r_1 and r_2 are the count rates, T is the duration of the measurement, and $\Delta\nu$ is the width of the frequency interval used for the measurement. This formula assumes that the background count rate is much smaller than the source count rate and that the cross coherence between the light curves is unity. The smallest time difference that can be measured is $\delta t_{min} = n_\sigma (2\pi\nu)^{-1}$ [arctan (S/N)]$^{-1} \approx n_\sigma (2\pi\nu)^{-1} (S/N)^{-1}$, where n_σ is the detection significance, in standard deviations.

The observation from Table 1 best suited for measuring time delays is the 1996 March 3 observation of 4U 1608−52, for which S/N ∼ 40 between energy channels of width ∼2 keV at energies below ∼12 keV. We divided the data containing strong ∼830 Hz QPOs into five energy channels covering the ranges 4–6, 6–8.2, 8.2–10.6, 10.6–16.6, and 16.6–30 keV and measured the time delay and cross-coherence function between all pairs of channels. The time delays are plotted in Figure 1 relative to the 4–6 keV channel. The sign convention is such that a positive time delay indicates that the higher energy channel lags behind the lower energy channel. The 8.2–10.6, 10.6–16.6, and 16.6–30 keV channels all lag the 4–6 keV channel with greater than 3 σ significance. The most significant lag (5 σ) is between the 4–6 and 10.6–16.6 keV channels: 27 ± 5 μs. The cross-coherence function between the channels is consistent with unity and is greater than 0.9 with 95% confidence for all channels.

We are also able to significantly constrain the time delay in the single QPO peak at ∼730 Hz observed 1996 March 16 in 4U 0614+091 and in the single QPO peak at ∼870 Hz observed 1996 May 29 in 4U 1636−53, as well as the cross coherence in 4U 1636−53. In both cases, to optimize S/N we divided the data into two energy channels. In 4U 0614+091 we find that the oscillations at 6.5–67 keV lag those at 2–6.5 keV by 26 ± 23 μs, and in 4U 1636−53 we find that the oscillations at 12.4–67 keV lag those at 8.7–12.4 keV by −2.7 ± 14 μs. For these two systems we thus have 95% confidence upper limits on the time delay, δt, of 45 μs (4U 0614+091) and 30 μs (4U 1636−53). The 95% confidence lower limit to the cross coherence is 0.85 in 4U 1636−53. The cross-coherence function of the QPOs in 4U 0614+091 could not be meaningfully

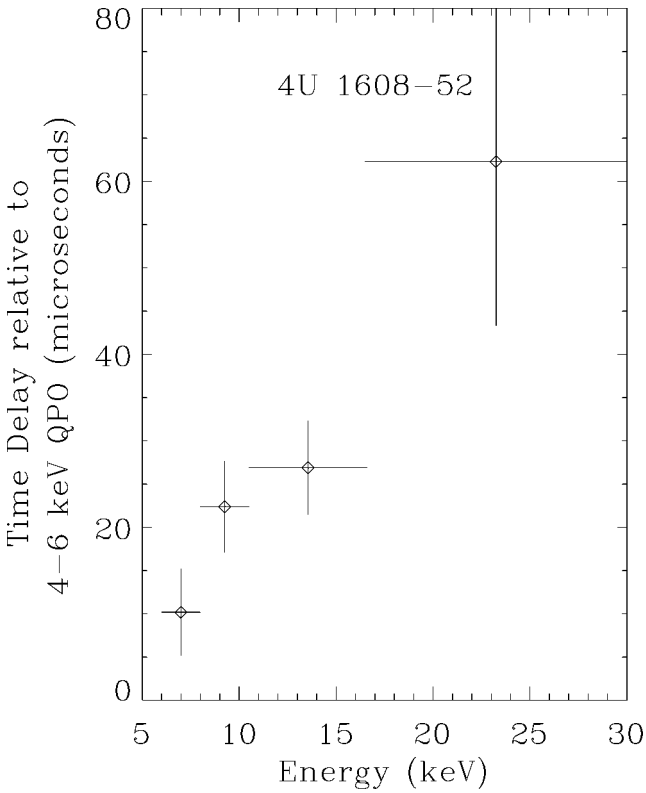

FIG. 1.—Time delays of the 830 Hz oscillation in 4U 1608−52 in four higher energy bands relative to the oscillation in the 4–6 keV band, measured in the frequency range 820–840 Hz on 1996 March 3.

constrained, since cross coherence is a fourth-order statistic with a large variance at small S/N. We attempted to investigate time lags in observations containing two simultaneous kilohertz QPO peaks. Our best candidate was a 1996 February 28 observation of 4U 1636−53 with QPOs at 900 and 1176 Hz (Wijnands et al. 1997). We were unable to measure the time delay in either of the two QPO peaks because of low S/N.

The small lags we see cannot be due to large ($\delta t \gg 1/\nu$) and variable time differences that average out to zero. If the lags were large and variable, we would find phase differences $\delta\phi = 2\pi\nu\,\delta t$ uniformly and randomly distributed in $[-\pi, \pi]$, large error bars $\Delta(\delta\phi) \sim \pi$, and small cross coherence.

4. DISCUSSION

We have measured time delays between the kilohertz QPOs at different photon energies in 4U 1608−52, 4U 0614+091, and 4U 1636−53. In the first source we find a significant hard lag, whereas in the latter two we find that any time delays are $\lesssim$45 μs. The QPOs investigated here have fractional rms amplitudes and widths comparable to those of the horizontal-branch oscillations in the Z sources, but their frequencies are 10–40 times higher, so we are sensitive to time lags 10–40 times smaller. In 4U 1608−52, the ~27 μs time lag is equivalent to a phase difference of ~0.13 rad, or about 8°.

The time lags we have measured can be used to derive general constraints on the X-ray production mechanisms in these systems (see Lamb 1988). It is important to consider these constraints in the larger context of the time lags, energy spectra, power spectra, and cross coherence between the oscillations at different photon energies. Any physical model should be consistent with all four of these statistical properties. If the X-ray spectrum is not formed predominantly by Compton scattering, then the ~800 Hz oscillation at 11–16 keV must be produced so that it lags the oscillation at 4–6 keV by ~27 μs in 4U 1608−52. Delays must be $\lesssim$45 μs in 4U 0614+091 and 4U 1636−53. The high value ($\gtrsim$0.85) of the cross coherence in 4U 1636−53 and 4U 1608−52 requires that if the source of photons responsible for the QPOs is physically extended, the lags in the emission process must be independent of location (Vaughan & Nowak 1997; Nowak & Vaughan 1996). Any model in which the QPOs are produced at the surface of a neutron star that is also a pulsar must explain why the QPOs are seen but the periodic oscillations are hidden.

We now consider models in which photons produced near the neutron star are upscattered by electrons in a region with optical depth $\tau \gtrsim 1$. Optically thin free-free emission in a scattering region $\lesssim$100 km in size supplies too few photons to account for the observed luminosity of the atoll sources, which is $\sim 0.1 L_{\rm Edd}$. Hence the photons must be produced in a self-absorbed region, such as the outer layers of the neutron star. Given the observed luminosities of these sources, any thermal emission from the neutron star peaks at ~1–2 keV. No such peak is observed, indicating that the scattering region has an optical depth of $\gtrsim$3. Models of this type provide a natural explanation for the X-ray spectra of these sources (see Lamb 1989; Psaltis, Lamb, & Miller 1995) and may also offer an explanation of their rapid X-ray variability (see Miller et al. 1997 for an overview). We analyze the generic properties of models of this type, avoiding special geometries or physical conditions.

The fractional rms amplitudes of the kilohertz QPOs can be used to place an upper bound on the sizes of emitting regions in all kilohertz QPO sources. Quite generally, the size of the region must be less than a few times $c/\nu_{\rm QPO}$, independent of the QPO mechanism, since radiation from different parts of the region have different path lengths to the observer, causing phase shifts that attenuate the QPO signal. If the radiation is scattered, the rms amplitude at infinity of a luminosity oscillation with frequency ν and amplitude A_0 at the center of a spherical region of radius a and optical depth τ is $A_\infty \simeq (2^{3/2}xe^{-x} + e^{-\tau})A_0$, where $x \equiv (3\pi\nu a\tau/c)^{1/2}$ (Kylafis & Phinney 1989). The ~800 Hz QPOs studied here have rms amplitudes of ~10%, so if they are luminosity oscillations the scattering region must be smaller than ~200 km if $\tau \sim 5$. If instead they are beaming oscillations, the scattering region must be smaller than ~100 km if $\tau \sim 5$. These bounds are almost independent of the electron temperature and bulk velocity in the scattering region, and they remain approximately valid for nonspherical regions.

The time lags reported here, if caused by upscattering, provide stringent constraints on the size, a, of the upscattering region. We first compute a rough, qualitative estimate of a. If photons with energy $E_{\rm in}$ are injected into a scattering region, where the electron temperature $T_e \gg E_{\rm in}/k_{\rm B}$, they will gain energy each time they scatter, so photons that escape with a higher energy E_2 emerge later than photons that escape with a lower energy E_1. The delay δt in the arrival time at a distant observer of photons of energy E_2 relative to photons of energy E_1 depends upon the geometry of the region and the spatial distribution of its electron density and temperature but will be $\sim \Delta u l/c$, where l is the photon mean free path and Δu is the difference in the average number of scatterings experienced by photons that emerge with energies E_1 and E_2. If $\Delta u \sim u$, where u is the average number of scatterings to escape from the cloud, then $\delta t \sim au/c\tau$, where $\tau = a/l$ is the optical depth. For

$\delta t \sim 27$ μs, $\tau \sim 5$, and $u \sim \tau^2$, the inferred size of the scattering region is a few kilometers.

To estimate the size of the region more quantitatively note that, if the scattering electrons are nonrelativistic, then after one scattering the average energy of a photon with initial energy $E_{\rm in}$ is $E \sim E_{\rm in} \exp(4k_{\rm B}T_e/m_ec^2)$, where m_e is the electron rest mass (see Rybicki & Lightman 1979). Therefore, the ratio of the energies of two photons that experience a different number of scatterings is $E_2/E_1 \sim \exp(4\Delta u k_{\rm B}T_e/m_ec^2)$. Solving this expression for Δu and using the above expression for δt yields

$$\delta t \sim \frac{a}{c\tau}\frac{m_ec^2}{4k_{\rm B}T_e}\ln\left(\frac{E_2}{E_1}\right) \qquad (1)$$

(see, e.g., Sunyaev & Titarchuk 1980). For 4U 1608−52, we have measured $c\,\delta t$ to be ~8 km for $E_1 = 5$ keV and $E_2 = 14$ keV, and hence $a \sim 8\tau(4k_{\rm B}T_e/m_ec^2)$ km.

Photons injected with energies $E_{\rm in} \ll k_{\rm B}T_e$ into a region with a Compton parameter $y \equiv 4k_{\rm B}T_e\tau^2/m_ec^2$ that is less than the saturation value $y_{\rm sat} \sim 10$ emerge with a spectrum that is roughly a power law with an exponential cutoff at $\sim 2k_{\rm B}T_e$. The count-rate spectra of the atoll sources indicate $k_{\rm B}T_e \gtrsim 10$ keV (White, Stella, & Parmar 1988), in which case a must be greater than $\sim\tau$ km. Compton upscattering produces hard time lags only if it is unsaturated, i.e., only if $y \lesssim y_{\rm sat}$, so a must also be less than $\sim 8(y_{\rm sat}/\tau)$ km. Combining these upper and lower limits, we find

$$5\left(\frac{\tau}{5}\right)\ {\rm km} \lesssim a \lesssim 16\left(\frac{y_{\rm sat}}{10}\right)\left(\frac{5}{\tau}\right)\ {\rm km}, \qquad (2)$$

where we have scaled the expressions to $\tau \sim 5$, the value suggested by models of the X-ray spectra and rapid X-ray variability of the atoll sources (see, e.g., Lamb 1989; Psaltis et al. 1995; Miller et al. 1997).

In this analysis, we have assumed that soft photons are injected at the center of a spherical region of uniform temperature and electron density. If any of these conditions are not satisfied, the bounds on the size of the Compton upscattering region are larger than those derived above. We have also assumed that $E_2 \ll 2k_{\rm B}T_e$. If instead $E_2 \sim k_{\rm B}T_e$, the energy change in each scattering of photons with energy near E_2 is significantly less than we have assumed, so δt is significantly greater than in equation (1) and the bounds on a are correspondingly smaller than estimated above. However, the value of E_2 used here (14 keV) is less than the ~20 keV lower bound on $2k_{\rm B}T_e$ inferred from the X-ray spectra of the atoll sources, so this effect is probably small. We expect that the upscattering region is in reality inhomogeneous and that the size of the upscattering region is closer to the lower bound rather than the upper bound in equation (2) (see Miller et al. 1997). This is natural since we know that 4U 1608−52 is a neutron star because it produces type I X-ray bursts (see Brandt et al. 1992 and references therein).

Compton upscattering by electron orbital motions may also be important in forming the X-ray spectra of these sources. If the radiation field is nearly isotropic and the typical orbital velocity of the electrons is V, the spectrum that emerges from the scattering region is roughly a power law up to a cutoff energy $E_c \sim m_ec^2(V/c)^2$ (Psaltis & Lamb 1997). For example, if $V/c \sim 0.15$, which can easily be attained in regions as close to the neutron star as we are considering, then $E_c \sim 10$ keV. If Compton upscattering by electron bulk motion is important, the time lags will depend upon the radial dependence of V, but the bounds on the size of the scattering region remain about the same.

In summary, the time lags we have measured indicate that the Compton upscattering region in 4U 1608−52 is between a few kilometers and a few tens of kilometers in size, i.e., comparable to the size of a neutron star.

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ERRATA

In the Letter "Discovery of Microsecond Time Lags in Kilohertz QPOs" by B. A. Vaughan, M. van der Klis, M. Méndez, J. van Paradijs, R. A. D. Wijnands, W. H. G. Lewin, F. K. Lamb, D. Psaltis, E. Kuulkers, and T. Oosterbroek (ApJ, 483, L115 [1997]), the reported time lags, while correct in magnitude, have a sign that is incorrect. We reanalyzed the data and checked the sign of our results using the hard lags in Cyg X-1 and GX 339−4 and the soft lags in the accreting millisecond pulsar SAX J1808.4−3658, as well as by using test signals. The true time delays for 4U 1608−52 are in the sense of the soft photons lagging the hard ones. Any lags in the reported energy and frequency ranges for 4U 0614+091 are between −80 and +15 μs and for 4U 1636−53 are between −50 and +25 μs (95% confidence), respectively, where a positive sign indicates a hard lag. This strengthens the conclusion of the Letter that in simple scattering models any time lags due to inverse Compton scattering are small and imply very small ($\lesssim$1–10 km) scattering geometries. The time-lag data provide no independent evidence for inverse Compton scattering affecting the X-rays in these sources; another mechanism, perhaps related to the generation of the QPOs, must be operating to produce the soft lags in 4U 1608−52.

In the article "The Protostellar Origin of a CS Outflow in S68N" by G. A. Wolf-Chase, M. Barsony, H. A. Wootten, D. Ward-Thompson, P. J. Lowrance, J. H. Kastner, and J. P. McMullin (ApJ, 501, L193 [1998]), the units for the last eight entries of Table 1 were inadvertently omitted during the editing process and the coordinate value for the second entry under "The Outflow" was incorrect. Below is the table as it should have appeared.

TABLE 1
S68N Source and Outflow Properties

Parameter	Value
The Source	
S68N[a] α(1950)	$18^h27^m15\overset{s}{.}63$
S68N[a] δ(1950)	$+01°14'42\overset{''}{.}0$
Distance[b] D (pc)	310
Bolometric luminosity L_{bol} ($L_\odot$)	5.0
S68N 450 μm flux (within 20″ aperture) F_ν (Jy)	25
S68N 850 μm flux (within 20″ aperture) F_ν (Jy)	3.3
The Outflow	
H_2O maser[c] (V_{LSR} = 8.5 km s^{-1}) α(1950)	$18^h27^m15\overset{s}{.}7513$
H_2O maser[c] (V_{LSR} = 12.4 km s^{-1}) α(1950)	$18^h27^m15\overset{s}{.}7506$
H_2O maser[c] (V_{LSR} = 8.5 km s^{-1}) δ(1950)	$+01°14'39\overset{''}{.}043$
H_2O maser[c] (V_{LSR} = 12.4 km s^{-1}) δ(1950)	$+01°14'39\overset{''}{.}154$
Assumed CS abundance (CS/H_2)	9×10^{-9}
Flow maximum radial extent R_{max} (pc)	0.045
Characteristic velocity V_{char} (km s^{-1})	6.5
Dynamical timescale $t_D = R_{max}/V_{char}$ (10^3 yr)	6.8
Outflow mass M_{flow} ($M_\odot$)	0.205
Outflow force (momentum flux) $F_{obs} = P/t_D$ ($M_\odot$ km s^{-1} yr^{-1})	2.0×10^{-4}
Mechanical luminosity $L_{mech} = E/t_D$ ($L_\odot$)	0.11
Inclination angle i (deg)	40–60

[a] Location of the 450 μm continuum emission peak.
[b] From de Lara, Chavarria-K., & López-Molina 1991.
[c] From H. A. Wootten 1995, private communication.