A Precessing Disc in OJ287?

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Abstract

Sillanpää, et al. (1996) have demonstrated that the AGN OJ287 has intensity peaks which recur with a period of about 12 years. I suggest that this is the result of the sweeping of a precessing relativistic beam across our line of sight. In analogy to Her X-1 and SS433, precession is attributed to the torque exerted by a companion mass on an accretion disc. Secondary maxima observed 1.2 years after two of these peaks may be evidence of nodding motion.

Subject headings: Galaxies: BL Lacertae Objects: OJ287 — Accretion, Accretion Discs
1. Introduction

Sillanpää, *et al.* (1996) reported, in confirmation of the prediction of Sillanpää, *et al.* (1988), that the AGN OJ287 has outbursts in visible light with an observed period of about 11.65 y (8.9 y in its rest frame at its cosmological redshift of 0.306). This extraordinary result marks the first confirmed periodicity of any extragalactic object, other than variable stars observed in nearby galaxies.

Several mechanisms, generally assuming a binary supermassive black hole, have been proposed which may explain this periodicity. Begelman, Blandford & Rees (1980) (henceforth BBR) suggested that accretion discs and jets surrounding a supermassive black hole may undergo geodetic precession in the gravitational field of a binary companion black hole. This process would produce uniform precession which would modulate a jet’s observed Doppler shift and its observed intensity. Typical estimates of the geodetic precession period are several hundred years, much longer than observed in OJ287.

Sillanpää, *et al.* (1988) suggested that the observed period might be the binary period itself, with the companion (another massive black hole, or conceivably a star) disrupting an accretion disc and modulating its accretion rate. These authors suggested a strongly eccentric and rapidly relaxing orbit, but such a short period orbit would probably have circularized (BBR). An inclined (to the accretion disc) circular orbit might be more plausible, with the companion disrupting the disc and stimulating accretion on each passage through it, implying an orbital period of twice the observed period. However, it is unclear how a local disruption or tidal perturbation in the outer portions of an accretion disc could produce a brief (≈ 0.01 of the orbital period) surge of accretion at its center. Further, a massive companion in an inclined orbit would make the disc’s axis precess about the total angular momentum axis and would deplete the disc of material at the radius of the companion’s orbit; a sudden and disruptive plunge of the companion through the disc is likely only if the companion’s orbit is very eccentric.

The observed narrow spikes of intensity suggest a relativistic beam sweeping close to
or across our line of sight, in accordance with models of OJ287 and similar objects which hypothesize such a beam directed nearly towards the observer. This paper proposes a model which attributes this beam geometry to the precession of an accretion disc driven by the gravitational torque of a companion mass. In §2 I review the properties of driven accretion discs, and compare them qualitatively to observations of OJ287. In §3 I attempt to constrain the parameters of OJ287. This requires consideration of the possible evidence for nodding motions in OJ287 and its implications. §4 contains a brief summary discussion.

2. Driven Precessing Accretion Discs

An accretion disc inclined to the orbital plane of a binary system will precess at the rate

$$\Omega_0 = -\frac{3}{4} \frac{G m_2}{a} \left( \frac{a_d}{a} \right)^2 \frac{\cos \theta_0}{(G m_1 a_d)^{1/2}},$$

(1)

where $m_1$ is the mass of the accreting object, $m_2$ the mass of its companion, $a$ their separation (assuming a circular binary orbit), $a_d$ the disc radius and $\theta_0$ the inclination of the disc to the orbital plane. The theoretical driven precession frequency $\Omega_0$ is distinguished from the observed precession frequency $\omega_{pre}$; $\Omega_0$ is a measure of the torques which drive the nodding motion, even if the actual precession has other contributions and occurs at a different rate (as is the case in SS433, for which $\Omega_0/\omega_{pre} \approx 2.1$). The physical mechanism is the same as that which drives the recession of the nodes of the Moon’s orbit, and was applied to the accretion disc in Her X-1 by Katz (1973) and to that in SS433 by Katz (1980). This Newtonian driven precession is, in general, much faster than geodetic precession.

Observations of Her X-1 and SS433 provide sensitive measures of the behavior of their precessing discs. Her X-1 is eclipsed by sharp-edged disc structures. Accurately observed Doppler shifts in SS433 permit accurate determinations of the orientation of its jets and disc. Long time series have permitted detailed investigation of these laboratories for the study of accretion disc dynamics, and the results may be compared to observations of OJ287:
1. The $Q$ of the precession, considered as an oscillator, is about 39 in Her X-1 (Baykal, et al. 1993) and about 75 in SS433 (Baykal, Anderson & Margon 1993). This is comparable to the $Q \sim 25$ implied by the scatter in intervals between peaks of OJ287 reported by Sillanpää, et al. (1988), and contrasts to orbital periods or geodetic precession periods, which should either be good clocks with very high $Q$ or show monotonically decreasing periods if dissipative processes shrink the orbit.

2. In addition to its mean precession there is an oscillation (“nodding”) in the disc’s orientation with frequency $2\omega_{\text{orb}} - 2\omega_{\text{pre}}$ (N.B.: the orbital frequency $\omega_{\text{orb}}$ is positive by convention and $\omega_{\text{pre}}$ is negative). In Her X-1 nodding produces preferred orbital phases for the X-ray source’s emergence from eclipse by the accretion disc and complex pre-eclipse dip behavior; in SS433 it produces a 6-day period in the Doppler shifts (Katz, et al. 1982, henceforth KAMG; Levine and Jernigan 1982). In OJ287 nodding may explain the secondary peaks observed 1.2 years after the main peaks in 1971 and 1983; only the driven precessing disc model naturally explains them. Flickering in the intensity of OJ287 makes it difficult to identify the nodding motion except near the peak. The secondary peaks are not explicable if the 12 year period is attributed either to the orbital period or to geodetic precession.

3. Parameters of OJ287

In order to apply the precessing disc model to OJ287 we should estimate the critical parameters $i$ and $\theta_0$, where $i$ is the inclination of the orbital angular momentum axis to the direction to the observer. Unfortunately, in contrast to SS433 no quantitative kinematic information is available for OJ287. We can, however, make some estimates, noting that the beam-width of radiation emitted by a relativistically moving object is $\sim 1/\gamma$, where $\gamma$ is its Lorentz factor of bulk motion (it is assumed to radiate isotropically in a frame which has this Lorentz factor with respect to the observer’s frame, although this is surely an oversimplified description of a cloud of relativistic electrons directed approximately in
our direction). In order that the observer be within the path of the beam we must have

$$|i - \theta_0| \lesssim 1/\gamma + \theta_n,$$

(2)

where $\theta_n$ is the amplitude of the nodding modulation of the precession angle.

In order to produce an intensity peak whose half-width (Sillanpää, et al. 1996) is a fraction $f \sim 0.01$ of the precession period requires a beam width $\sim 2\pi f \sin \theta_0$, where a factor-of-two uncertainty is introduced by the fact (KAMG) that nodding multiplies the rate of precession around its mean path by a factor varying (with the nodding frequency) from 0 to 2, as well as introducing periodic oscillations in $\theta$ about its mean value $\theta_0$. This factor, as well as the comparative intensities of the primary and secondary peaks (and their exact separation) depend on the relative phases of the nodding and orbital motion, and will not repeat from cycle to cycle unless the motions happen to be commensurate. Then

$$\gamma \sim (2\pi f \sin \theta_0)^{-1} \sim 50,$$

(3)

(where $\theta_0 = 20^\circ$ is used in analogy to SS433, the only system in which $\theta_0$ is known). This is larger than the $\gamma \sim 10$ typically inferred from radio measurements of superluminal expansion in AGN, but is rather uncertain; source selection on the basis of visible intensity measurements may introduce a bias towards large Lorentz factors so that the very luminous OJ287 may be characterized by larger $\gamma$ than most AGN. In addition, visible emission may result from more relativistic motion than that characterizing the more extended regions (and less energetic particles) producing radio emission.

If the secondary maximum in intensity observed 1.2 y after the 1971 and 1983 peaks is attributed to nodding then the orbital period is determined as well as the precessional period, and it becomes possible to determine other parameters of OJ287. The nodding amplitude is (KAMG)

$$\theta_n = \frac{|\Omega_0| \tan \theta_0}{2(\omega_{orb} - \omega_{pre})},$$

(4)
If $\Omega_0 = \omega_{\text{pre}}$ (likely in a supermassive black hole binary, for which the mechanisms leading to $\Omega_0 \neq \omega_{\text{pre}}$ in mass transfer binary stars are inapplicable) then the observed parameters, attributing the secondary intensity peak to nodding motion, imply $\theta_n \approx 0.11 \tan \theta_0$. The precession amplitude $\theta_0$ is unknown, but again assuming $\theta_0 = 20^\circ$ as in SS433 suggests $\theta_n \sim 0.04$. If the secondary peak is not attributable to nodding then $\omega_{\text{orb}}$ is unknown; analogy to Her X-1 and SS433 would then suggest an orbital period in the range 0.5–1 y and $\theta_n \approx (0.02–0.04) \tan \theta_0 \sim 0.007–0.014$.

Combining Eq. (3) and our estimated $\theta_n$ implies that $i$ and $\theta_0$ must be equal to within roughly $\pm 3^\circ$ (the actual condition is uncertain because $\theta_0$ is unknown). Approximate equality between these two angles is required in any precession model which is to explain the narrowness of the periodic intensity peak (a broader peak would lead to a lower estimated $\gamma$ and a less stringent constraint on $|i - \theta_0|$), and does not depend on the precession mechanism. The permitted angular range, roughly a third of $\theta_0$, is broad enough to be plausible, in part because the presence of nodding makes Eq. (2) less stringent than it would otherwise be; nodding increases the width of the swath about the mean precession path over which the beam is swept. Intensity selection introduces a strong bias in favor of detection of sources whose beams are, at least occasionally, directed towards the observer.

Nodding produces two periodic terms in the jet’s Doppler shift. Their amplitudes (in the redshift $z \equiv \Delta \lambda/\lambda_0$) are (KAMG)

$$A(2\omega_{\text{orb}} - 2\omega_{\text{pre}}) = \frac{\gamma v \Omega_0 \sin \theta_0 \tan \theta_0 \cos i}{2(\omega_{\text{orb}} - \omega_{\text{pre}})},$$

$$A(2\omega_{\text{orb}} - \omega_{\text{pre}}) = \frac{\gamma v \Omega_0 \sin \theta_0 \sin i}{2(\omega_{\text{orb}} - \omega_{\text{pre}})}.$$  (5)

The ratio of these amplitudes is $\tan \theta_0 \cot i$. In SS433 the second of these amplitudes is dominant because $i$ is nearly $90^\circ$ but $\theta_0$ is small, but in OJ287, with $i \approx \theta_0$ expected, both amplitudes should be comparable. However, in OJ287 the observed signal is an intensity which is proportional to $(1 + z)^{-(2+\alpha)}$, where $\alpha$ is the spectral index (typically $\alpha \approx 0.5$), and hence is narrowly peaked around the minimum in $1 + z$ when the beam points nearly...
directly towards the observer, in contrast to SS433 in which the periodic variations in Doppler shift are directly observed throughout the precessional cycle. The implied orbital period in the source frame is 2.1 y or 2.3 y, depending on which of the two periods in Eq. (5) is identified with the observed 1.2 year interval.

The separation of the two black holes is

\[
a \approx 1.1 \times 10^{16} \left( \frac{m_1 + m_2}{10^8 M_\odot} \right)^{1/3} \text{ cm.}
\]  

(6)

In Eq. (6) the lower of the two possible nodding frequencies was assumed, although the difference between them is less than the error in determination of the separation between the peaks because of flickering in the intensity. The lifetime to gravitational radiation (BBR) is then

\[
t_{gr} \approx 4 \times 10^5 \left( \frac{m_1}{10^8 M_\odot} \right)^{-5/3} \frac{(1 + \mu)^{4/3}}{\mu} \text{ y,}
\]  

(7)

where \( \mu \equiv m_2/m_1 \).

Comparison of the precessional to the orbital period permits, using Eq. (1), estimation of the size of the precessing disc. It approximately fills the Roche lobe, and is about the maximum size permitted for a stably orbiting ring (Bahcall, et al. 1974); for such a large ring Eq. (1) is not accurate and the ring may be smaller than indicated and have more complex motion. OJ287 differs from Her X-1 and SS433, whose much smaller precessing rings fit well within their Roche lobes. This is not surprising, for in a mass transfer binary the accretion disc is fed by matter from the companion star through its wind or Roche lobe overflow with comparatively little specific angular momentum. In an AGN accretion occurs from an extended region outside the companion’s orbit, fed by distant stellar disruptions and mass loss with large specific angular momentum with respect to the accreting mass. The secondary mass may then be less effective in disrupting the outer parts of the disc than in a mass transfer binary, especially if \( \mu \ll 1 \).

4. Discussion
The observation of periodicity in OJ287, the AGN with perhaps the best long time series of brightness data, suggests that this phenomenon is common. Similarly, the best observed eclipsing accretion disc (that of Her X-1) and the only observed subrelativistic jet source (SS433) show precession, suggesting that precession is frequent, if not universal, in discs: wherever the data are good enough to reveal precession, it is found.

Can this be an accident? In binary X-ray sources it has been suggested (Katz 1973) that precession may be self-excited as the accretion disc shadows the secondary star and influences the geometry and angular momentum of radiation-driven mass transfer; precession would then be expected whenever the accreting object is luminous. This mechanism is probably inapplicable to binaries composed of two black holes. In an AGN there is no a priori reason to expect the angular momentum of accreted gas, whose origin is stars and interstellar matter in the galactic nucleus, to be aligned with that of the orbit of the binary black holes, implying that an accretion disc should generally be inclined to its binary’s orbital plane and should therefore precess.

It is still remarkable that OJ287 has a compact black hole binary of limited life expectancy (Eq. 7) during the period (probably brief compared to the age of the Universe) during which it is a luminous AGN. This suggests that the presence in a binary of the supermassive black hole may cause AGN activity, rather than just being accidentally associated with it. It is possible to speculate that each black hole and its surrounding accretion disc may facilitate accretion by the other black hole and disc. The gravitational or hydrodynamic mechanisms by which this may occur are surely complex, but may have their origin in the fact that the gravitation of a binary does not exert a central force, and does not conserve the angular momentum of matter near it.

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