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LETTERS TO NATURE

A test of the massive binary black hole hypothesis: Arp 102B

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The emission-line spectra of several active galactic nuclei (AGNs) have broad peaks which are significantly displaced in velocity with respect to the host galaxy. An interpretation of this effect in terms of orbital motion of a binary black hole predicts periods of a few centuries[1,2]. Here we point out that recent measurements of the masses and sizes of many low-luminosity AGNs imply orbital periods much shorter than this. In particular, we find that the elliptical galaxy Arp 102B is the most likely candidate for observation of radial velocity variations; its period is expected to be ~3 yr. We have monitored the Hα line profile of Arp 102B for 5 yr without detecting any change in velocity, and thus find that a rather restrictive observational test of the massive binary black hole hypothesis already exists, albeit for this one object.

Gaskell's estimate of a period of a few centuries[1] is based upon the reasonable assumption that the binary separation has to be at least as large as the typical radius of the broad-line region (0.1-1 pc) for separate emission-line peaks to be discernible. Kepler's third law yields $P=550R_{18}^{3/2}M_9^{-1/2}$ yr, where R_{18} is the binary separation in units of 10^{18} cm and M_9 is the sum of the black hole masses in units of $10^9\,M_\odot$. The expected velocity, assuming equal masses, is $v=1{,}800\,M_9^{1/2}R_{18}^{-1/2}$ km s^{-1}, in agreement, for a pair of $10^9\,M_\odot$ black holes, with observed displacements of 2,000-3,000 km s^{-1}. Although these estimates for M and R are representative of luminous quasars, several of the objects in which the displaced-peak phenomenon has been observed are better characterized in terms of absolute luminosity as Seyfert or radio galaxies. The well-known example[3] 3C390.3 has redshift $z=0.057$, $M_{\rm abs}=-22.3$, and X-ray luminosity[4] $\sim 3\times 10^{44}$ erg s^{-1}. A cross-correlation analysis of the continuum and emission-line light curves indicates that the broad-line region in 3C390.3 is only 10^{17} cm in radius[5], so an orbital period could be as small as 15-20 yr. Recent observations of X-ray variability in Seyfert galaxies[6] have provided estimates of the black hole size via light-travel time arguments, which seem to indicate that the mass is proportional to the X-ray luminosity[7]. An equivalent statement is that the luminosity is a fixed fraction of the Eddington value; in this case the bolometric luminosity is $10^{-2.0\pm0.5}L_{\rm Edd}$ (ref. 7). Thus at fixed orbital velocity, the lower luminosity object is likely to have the shorter period. Several Seyferts have been seen to vary significantly in X-rays on time scales of an hour[8-12], which implies $M\leq 10^8\,M_\odot$. In addition, correlated continuum and line variations which have been seen in some Seyfert galaxies indicate that the broad-line region may be of the order of 1 light week in size[13], which would permit still shorter orbital periods to be detected.

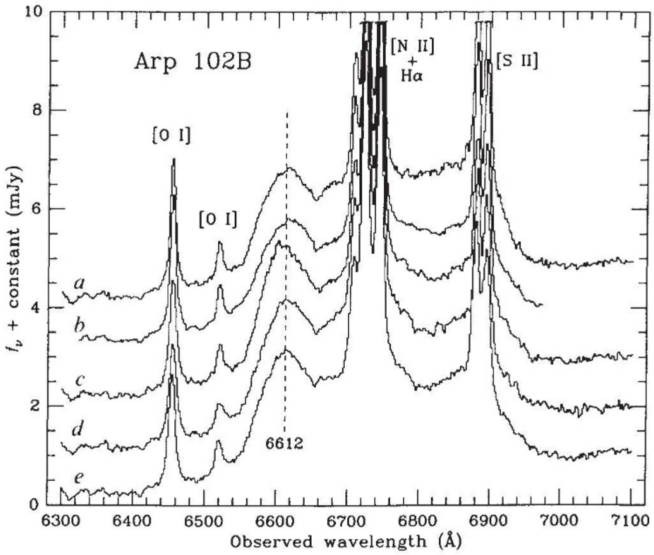

Fig. 1 CCD spectra of the nucleus of Arp 102B obtained on (*a*) 19 June 1983, (*b*) 28 June 1985, (*c*) 13 July 1986 and (*d*) 4 May 1987. Spectrum (*e*) is an average of two observations made on 8 and 12 August 1987, which are indistinguishable within noise limits. The ordinate scale refers to spectrum (*c*). All other spectra were scaled to the average flux of (*c*) and are plotted with additive offsets of 1 or 2 mJy. The vertical dashed line is at 6,612 Å, the average wavelength of the prominent blueshifted peak in the profile of Hα.

Arp 102B ($M_{\rm abs}=-21$, $z=0.0244$), an elliptical AGN of modest radio[14] and X-ray[15] luminosity, is the best candidate we know of for a test of the binary hypothesis. Its broad Hα line profile[16,17] is very similar to that of 3C390.3, with a prominent peak blueshifted by 5,000 km s^{-1} from the rest frame of the galaxy as defined by either the narrow emission lines or the stellar continuum. The X-ray luminosity[15] is only 8.6×10^{42} erg s^{-1}, the emission-line luminosities scale appropriately[16], and the optical continuum is dominated by starlight. Although no observations for X-ray variability have been made, it is reasonable to assume that the mass of the black hole in Arp 102B is $\leq 10^8\,M_\odot$, similar to that derived[7] for virtually all Seyfert galaxies having $L_x \leq 10^{43}$ erg s^{-1}. Given a binary with equal masses, Kepler's third law can be recast as $P\leq 2.7M_8(v\sin i)_{5,000}^{-3}$ yr, where i is the inclination angle of the orbit with respect to the plane of the sky, and $(v\sin i)_{5,000}$ is the observed radial velocity in units of 5,000 km s^{-1}. The small inferred mass, together with the relatively large radial velocity (which is of course only a lower limit to the orbital velocity), conspire to bring the predicted period within the span of a few observing seasons.

Table 1 Spectroscopy of Arp 102B

UT date	Telescope or reference	Resolution (Å)	Wavelength of displaced peak (Å)
6 Jun 1982	Ref. 16	10	$6,608 \pm 7$
19 Jun 1983	Palomar 5-m	2	$6,615 \pm 3$
15 Sep 1983	Palomar 5-m	15	$6,610 \pm 5$
28 Jun 1985	Palomar 5-m	2	$6,616 \pm 4$
13 Jul 1986	Lick 3-m	7	$6,606 \pm 4$
4 May 1987	Lick 3-m	7	$6,613 \pm 3$
8 Aug 1987	Lick 3-m	7	$6,615 \pm 4$
12 Aug 1987	Lick 3-m	7	$6,612 \pm 3$

In fact, we have been recording high-quality spectra of the Hα line of Arp 102B since June 1983, using CCD (charged couple device) spectrographs on the 5-m Hale telescope at Palomar Observatory and the 3-m Shane reflector at Lick Observatory. Most of the observations were made in photometric conditions. The slit width was 2″ and the atmospheric seeing was 1″–1.5″. Normal procedures[18] were used to calibrate and analyse the spectra. In addition, small errors in the wavelength scale were eliminated with the help of atmospheric emission lines and narrow emission lines in Arp 102B. An accurate redshift, derived from the narrow lines in several of the best spectra, is 0.02438 ± 0.00006.

The broad component of Hα (Fig. 1) departs dramatically from the gaussian or logarithmic profile normally seen in AGNs. Although the profile varies with time, in all cases there is a well-isolated hump on the blue side of the line. A less prominent hump is also visible on the red side, but we will not analyse it here because the narrow [S II] emission lines contaminate it.

It is clear that the wavelength of the blue hump remains virtually constant. Asymmetries in this hump make its exact wavelength difficult to define, but the difference between the peak and centroid is rarely more than a few ångströms, so an average of these quantities is adopted. Our measurements of the wavelength of the hump are listed in Table 1. The quoted errors are about one standard deviation. We also list a measurement from a published spectrum[16] which extends the temporal coverage to 1982. The measurements are consistent with a constant wavelength of 6,612 Å, which translates to a velocity of 4,980 km s^{-1} in the frame of the galaxy. The wavelengths display no systematic variation with time.

We have measured the velocity of the displaced broad-line peak to an accuracy of about 200 km s^{-1}, which is 4% of the observed velocity. In 5 years there have been no detectable changes in velocity at the 4% level; hence, we can place an upper limit of $2 \cos^{-1} 0.96 = 32°$ on $\Delta\phi$, the change in phase angle of the hypothesized binary. This translates to a lower limit of 55 yr for an orbital period. Thus, we can claim confidently that either the mass is greater than $2 \times 10^9 M_\odot$, or Arp 102B is not a spectroscopic binary.

A similar analysis of possible evidence for a binary black hole in the Seyfert galaxy NGC5548 relied on a careful decomposition of the line profile into two components which are stationary in wavelength[19]. On this interpretation, the binary period of NGC5548 is at least 110 yr and the mass is greater than $4 \times 10^7 M_\odot$. Since this mass limit is not in conflict with observations or models of NGC5548, the data on this galaxy are not yet a test of Gaskell's hypothesis, but are consistent with it.

Of course, the weak link in this method is the estimation of the unknown mass from the X-ray luminosity, in the absence of variability data. Although the proportionality between mass and X-ray luminosity seems to be good to within a factor of three for type 1 Seyfert galaxies[6], unusual elliptical galaxies such as Arp 102B have not been studied as carefully for X-ray variability. Ellipticals may well be underluminous at X-ray energies compared with Seyferts of the same central mass. In fact, the X-ray luminosity of 3C390.3 has declined steadily by more than a factor of 10 in the past 15 yr (ref. 4), so it is difficult to use this quantity as a meaure of the mass. The fact that most of the displaced-peak objects are radio loud[1] may cast doubt upon the adoption of results gleaned from a largely X-ray selected (mostly radio quiet) sample[6]. Nevertheless, future X-ray observations of Arp 102B could, in principle, settle the question sooner than continued optical monitoring. Any observation of substantial variations in less than 8 h would imply that $M \leq 10^9 M_\odot$, eliminating the spectroscopic binary hypothesis.

Even a binary period of 55 yr, which is barely consistent with the current observational data, poses an additional theoretical difficulty. The corresponding separation of $\sim 3 \times 10^{17}$ cm is comparable with the radius of 5×10^{17} cm within which gravitational radiation takes over as the dominant force in the dynamical evolution[2]. Gravitational radiation shrinks this orbit on a time scale of 2×10^7 yr (ref. 2), much less the expected time of $\geq 10^9$ yr spent at larger separations during which the evolution is controlled by dynamical friction and gas accretion[2]. Thus, it is somewhat unlikely that one of only a handful of binary black holes would be observed in a state of small separation. On the other hand, there could be many more binaries of larger separation, such as NGC5548, which have gone unnoticed, making the small separation in Arp 102B less improbable.

Arp 102B forms an ideal test for Gaskell's hypothesis that binary black holes are formed by capture during collisions between galactic nuclei, one of which is a dwarf elliptical[20]. Although not a dwarf, Arp 102B is clearly an elliptical galaxy which has interacted with a disturbed spiral companion[21]. Only the elliptical currently has an active nucleus, so that the detection of a binary black hole would be strong evidence in favour of the capture theory. On the other hand, if continued monitoring of Arp 102B restricts the parameters of the binary model until it beomes implausible, another explanation of the unusual line profile will have to be found.

Perhaps models involving ordered motion in an accretion disk or jet should be considered. Some U Geminorum stars show double-peaked line profiles, but these tend to appear at small velocity, indicating an origin in the outer part of the disk[22-24]. For example, U Gem[22] had peaks separated by 1,100 km s^{-1}, but the full width of the line is 5,000 km s^{-1}. The best-fit disk model for U Gem has a ratio of inner to outer radius of ~ 0.04. By contrast, the displaced peaks in Arp 102B and other AGNs occur near the maximum velocity of the profile. Models for line profiles from a rotating disk in quasars have been calculated with relativistic effects included[25,26]. The line profile of Arp 102B is similar to disk models in which the ratio of inner to outer radius is ~ 0.3. The slight asymmetries could be accounted for by relativistic effects. Oke[27] has also suggested that a disk could be responsible for the displaced peaks in 3C390.3.

Alternatively, the displaced peaks may be due to material entrained in a pair of jets emerging along the axis of the disk. If the jets are longer than the disk radius, then both blue and red peaks should be observed. If the jets are short and the disk is optically thick, then only the blue peak is expected to be visible. This is analogous to the interpretation of the X-ray iron line in SS433, which shows only the blueshifted component[28]. In any case, the tendency of displaced peaks to be found in radio-loud objects is undoubtedly a clue to their origin, as is the unusually flat profile which characterizes the undisplaced portions of the lines in Arp 102B and 3C390.3.

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A possible 35-minute periodicity in the OJ 287 active galactic nucleus at 7-mm wavelength

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BL Lacertids are a class of active galactic nuclei (AGNs) characterized in part by flat radio spectra and rapid flux variability on time scales of weeks to days, at centimetre to optical wavelengths[1]. One such object, OJ 287, exhibits very short time-scale (minutes) nonperiodic variations in infrared and centimetre flux, as well as in optical polarization[2–4]. Over the past fifteen years, there have also been reports of short term (tens of minutes) periodic[5–8] modulation of the emission from OJ 287 at a variety of wavelengths; these periodicities have proved elusive to confirm[3,9], perhaps because they are inherently sporadic. Because the presence of periodic flux variations strongly constrains the nature of the central source within an AGN, the report of periodic variability in OJ 287 with a stable 15.7-min period detected at multiple frequencies and using different telescopes[8], prompted us to undertake observations of this object at 7-mm wavelength. In this letter, we report detection in February 1986 of a weak (4% amplitude), 35-min flux modulation of OJ 287, whose statistical significance we estimate to be ~97%. Nearly one year later, observations of the same source revealed no periodicities between 4 and 300 min with amplitudes greater than 2%.

Observations of five compact radio sources including OJ 287 were made during two days in February 1986 with the 14 m FCRAO (Five College Radio Astronomy Observatory) radio telescope operating at a frequency of 42.6 GHz. Additional observations of OJ 287 alone were also made on 1987 January 27, for reasons described below. The cooled 7-mm receiver[10] had an instantaneous bandwidth of approximately 350 MHz and was operated in double sideband mode with an intermediate frequency of 1.4 GHz. The system temperature was measured every few scans using an ambient-temperature absorbing vane[11]. In order to achieve maximum baseline stability, all sources were observed by beam chopping at 15 Hz against blank sky displaced about 6 arc min in azimuth from the source position, and alternating the main and reference beams on source every 12 s. Each scan consisted of a pair of such cycles, giving a total integration time of 48 s. Because the FCRAO antenna has an altazimuth mounting, the approximately 15-s overhead time for each scan (the time required to move alternately between the source and reference position, an interval which depends upon the source elevation) varied as the sources moved across the sky. Combined with the calibration measurements carried out every few scans, this produced an irregularly-sampled data series for each source. The irregularity of the sampling reduces sidelobes in the spectral window which could cause spurious features in the periodogram analysis[12]. Table 1 shows the sources and dates of observation.

The data for each source were analysed using the periodogram technique developed by Scargle[13] and elucidated by Horne and Baliunas[14]. The method allows one to assign a significance level to peaks in the estimated power spectrum of an irregularly-sampled data stream, provided that the time-series can be regarded as consisting of uncorrelated gaussian noise. Because no observational data can be expected to satisfy completely such a stringent statistical prerequisite (the power spectrum of virtually any astronomical time series will always be slightly 'red', owing to the presence of long-term environmental and receiver

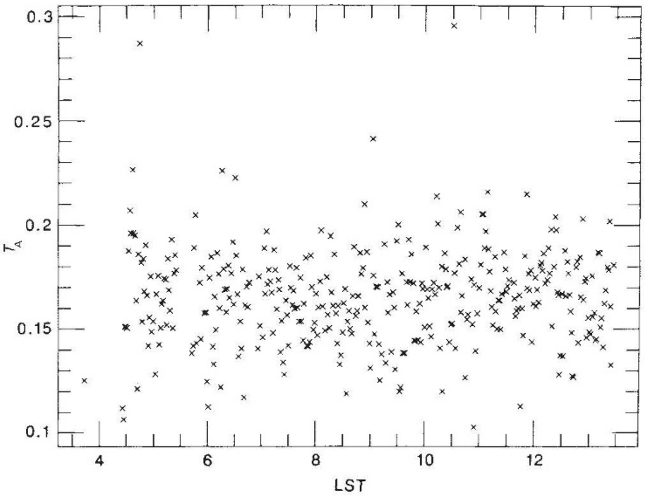

Fig. 1 Antenna temperatures for OJ287 measured on the morning of 1 Feb. 1987. The mean value is 0.165 ± 0.001 K. The typical error in a single measurement is 0.016 K.

Table 1 Summary of observations

Date	Source	Periods examined (min)	N*	Period detected (min)	Amplitude (%)	p† (%)
1 Feb. 1986	OJ 287	3-300	356	35	4	<3
	BL Lac	2-20	43	—	<40	70
	3C84	3-120	141	—	<1	40
	SGR AW	3-50	67	—	<2	20
16 Feb. 1986	SGR AW	4-100	111	—	<1	70
	1921-29	4-40	40	—	<7	50
27 Jan. 1987	OJ 287	4-300	264	—	<2	75

* Number of data points in time series.
† Probability that largest peak in periodogram is due to gaussian noise.