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GSN 069 – A tidal disruption near miss

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ABSTRACT

I suggest that the quasi-periodic ultrasoft X-ray eruptions recently observed from the galaxy GSN 069 may result from accretion from a low-mass white dwarf in a highly eccentric orbit about its central black hole. At $0.21 M_{\odot}$, this star was probably the core of a captured red giant. Such events should occur in significant numbers as less extreme outcomes of whatever process leads to tidal disruption events. I show that gravitational radiation losses can drive the observed mass-transfer rate, and that the precession of the white dwarf orbit may be detectable in X-rays as a superorbital quasi-period $P_{\text{super}} \simeq 2$ d. The very short lifetime of the current event, and the likelihood that similar ones involving more massive stars would be less observable, together suggest that stars may transfer mass to the low-mass SMBH in this and similar galaxies at a total rate, potentially making a significant contribution to their masses. A similar or even much greater inflow rate would be unobservable in most galaxies. I discuss the implications for SMBH mass growth.

Key words: black hole physics – galaxies: active – X-rays: galaxies – supermassive black holes.

1 INTRODUCTION

Miniutti et al. (2019) have recently discovered large-amplitude (factors ~ 100) quasi-periodic X-ray eruptions from the low-mass black hole ($M_1 \sim 4 \times 10^5 M_{\odot}$) galaxy nucleus GSN 069. These each last a little more than 1 h, with a characteristic recurrence time $\simeq 9$ h. The emission has an ultrasoft blackbody spectrum with peak temperature and luminosity $T \simeq 10^6$ K, $L \simeq 5 \times 10^{42}$ erg s⁻¹. These imply a blackbody radius $R_{\text{bb}} = 9 \times 10^{10}$ cm, slightly larger than the gravitational radius $R_g = GM_1/c^2 = 6 \times 10^{10}$ cm of the black hole.

The very large amplitudes and short time-scales of the eruptions are difficult to explain except as mass-transfer events. The quasi-periodic repetitions suggest that mass overflowing from a star in an elliptical 9-h orbit about the black hole triggers powerful instabilities in the accretion disc at each pericentre passage. Hysteresis effects probably account for the departure from strict periodicity in the X-ray emission, as in stellar mass systems of this type.

2 MASS TRANSFER

Adopting this view, we have significant constraints on the orbiting star. The orbital semimajor axis is

$$a = 1 \times 10^{13} m_{5,6}^{1/3} P_9^{2/3} \text{ cm}, \quad (1)$$

where $m_{5,6}$ is the black hole mass M_1 in units of $4 \times 10^5 M_{\odot}$ and P_9 is the orbital period in units of 9 h. The tidal lobe of the orbiting star, of mass M_2 , is

$$R_{\text{lobe}} \simeq 0.46(M_2/M_1)^{1/3} a(1-e) \simeq 6.2 \times 10^{10} m_2^{1/3} (1-e) \text{ cm}, \quad (2)$$

where $m_2 = M_2/M_{\odot}$, e is the eccentricity, and I have adopted the prescription of Sepinsky et al. (2007) for tidal overflow in eccentric binaries (see also Dosopoulou & Kalogera 2016a,b). Since the star's radius $R_2 = r_2 R_{\odot}$ must equal R_{lobe} at pericentre, it must currently obey the constraint

$$r_2 = 0.89 m_2^{1/3} (1-e) \quad (3)$$

(note that this is *not* the mass–radius relation of the star, but simply requires that that relation must give values of r_2 and m_2 obeying equation (3) at the present epoch).

The gas lost from the orbiting star at pericentre passage circularizes at radius

$$R_{\text{circ}} \sim a(1-e) \simeq 10^{13} (1-e) \text{ cm}, \quad (4)$$

resulting in the formation of an accretion disc of outer radius $R_d \sim R_{\text{circ}}$.

I now ask if this kind of binary system can generate the very large mass-transfer rates required to explain the accretion luminosity. I assume that the observed rate given by the repeated outbursts is representative of the evolutionary mean, and justify this assumption later.

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For a typical black hole accretion efficiency of 10 per cent, the X-ray eruptions require a mass-accretion rate $\sim 5 \times 10^{22} \text{ g s}^{-1}$ at peak. Averaging these over the full 9-h cycle gives a mean mass-transfer rate

$$-\dot{M}_2 \simeq 10^{-4} M_\odot \text{ yr}^{-1}, \quad (5)$$

and so a mass-transfer time-scale

$$t_{\dot{M}} \sim -M_2/\dot{M}_2 \sim 10^4 m_2 \text{ yr}. \quad (6)$$

In general, there are only two ways to drive significant mass-transfer rates in a binary system: either the mass-losing star, which fills its tidal lobe at pericentre, must expand on the time-scale $t_{\dot{M}}$, or the binary must lose orbital angular momentum on this time-scale.

The first possibility is very unlikely: No known star has nuclear or thermal time-scales as short as equation (6), and dynamical time-scale mass transfer implies a time-scale $t_{\dot{M}}$ of only a few orbits, probably resulting in a common envelope, contrary to observation. So the system must instead lose orbital angular momentum on the time-scale $t_{\dot{M}}$.

The only likely mechanism for this is gravitational radiation (GR), which is potentially very efficient here because of the short orbital period and high total mass. The system then resembles a drastically speeded-up and eccentric version of short-period cataclysmic variable (CV) evolution. This is a long-studied area, (e.g. Faulkner 1971; Paczyński & Sienkiewicz 1981; see King 1988, for a review). Hameury et al. (1994), Dai & Blandford (2013), and Linnal & Sari (2017) discuss low-mass stars in circular orbits around SMBH.

For an eccentric orbit, the quadrupole GR loss rate is given by

$$\frac{\dot{J}}{J_{\text{GR}}} = -\frac{32}{5} \frac{G^3}{c^5} \frac{M_1 M_2 M}{a^4} f(e), \quad (7)$$

where J is the orbital angular momentum, $M = M_1 + M_2$ the (constant) total mass, and

$$f(e) = \frac{1 + \frac{73}{24}e^2 + \frac{37}{96}e^4}{(1 - e^2)^{7/2}} \quad (8)$$

(Peters & Mathews 1963). This shrinks the semimajor axis a while reducing the eccentricity more rapidly. These quantities are related by

$$a = \frac{c_0 e^{12/19}}{1 - e^2} \left(1 + \frac{121}{304} e^2 \right)^{870/2299} \quad (9)$$

(Peters 1964), where c_0 is a constant set by the initial value of a . We see that for extreme eccentricities $e \sim 1$ (i.e. $1 - e < 1$) we have

$$a \propto \frac{1}{1 - e^2} \sim \frac{1}{2(1 - e)}, \quad (10)$$

so we set

$$a = \frac{1 - e_0}{1 - e} a_0, \quad (11)$$

where $a_0 = 1 \times 10^{13} M_{5.6}^{1/3} P_9^{2/3} \text{ cm}$ and $e_0 \simeq 1$ are the current semimajor axis and eccentricity, respectively.

This implies that the pericentre separation

$$a(1 - e) \simeq a_0(1 - e_0) \quad (12)$$

remains almost constant when $e \sim 1$ – this is reasonable, since the GR emission is effectively confined to a point interaction at

pericentre. From equation (10) the orbital angular momentum

$$J = M_1 M_2 \left(\frac{Ga}{M} \right)^{1/2} (1 - e^2)^{1/2} \simeq M_1 M_2 \left(\frac{Ga_0}{M} \right)^{1/2} (1 - e_0^2)^{1/2} \quad (13)$$

simply varies as $J \propto M_1 M_2$. Logarithmic differentiation now gives

$$\frac{\dot{J}}{J} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} = \frac{\dot{M}_2}{M_2} \left(1 - \frac{M_2}{M_1} \right) \simeq \frac{\dot{M}_2}{M_2} \quad (14)$$

so that the current GR-driven mass-transfer rate is

$$-\dot{M}_2 \simeq 1 \times 10^{-7} m_{5.6}^{2/3} P_9^{-8/3} \frac{m_2^2}{(1 - e_0)^{7/2}} M_\odot \text{ yr}^{-1}, \quad (15)$$

where e is set =1 except in factors $(1 - e)$.

The theoretical rate (equation 15) gives the evolutionary mean mass transfer, evaluated over the time t_{lobe} the tidal lobe takes to move through one density scale height of the star. This is typically about $10^{-4} R_2$ near the inner Lagrange point (Ritter 1988), so here

$$t_{\text{lobe}} \sim 10^{-4} \frac{R_2}{\dot{R}_2} \sim 10^{-4} \frac{M_2}{|\dot{M}_2|} \sim 0.1 \text{ yr}. \quad (16)$$

Normally t_{lobe} is far longer than the observing time-scale, but here (uniquely), this is reversed because the mass-transfer time-scale is very short. The currently observed accretion rate is a good indicator of the long-term evolutionary mean, as asserted above.

3 THE ORBITING STAR

The work of the last Section gives two constraints (equations 3 and 15), which simultaneously fix the mass of the orbiting star and the eccentricity e . For a plausible identification, these values must be consistent with a physically reasonable mass–radius relation. The extremely short mass-transfer time-scale $t_{\dot{M}} \sim 10^4 \text{ yr}$ already tells us that this must either be set by the adiabatic reaction of a non-degenerate star to adiabatic mass loss (cf. Dai, Blandford & Eggleton 2013), or correspond to a degenerate star (e.g. a white dwarf).

First, to provide the deduced mass-transfer rate $\sim 10^{-4} M_\odot \text{ yr}^{-1}$, equation (15) requires

$$\frac{m_2^2}{(1 - e_0)^{7/2}} = 10^3, \quad (17)$$

or

$$1 - e_0 \simeq 0.14 m_2^{4/7}. \quad (18)$$

Substituting this into equation (3) gives

$$R_2 = r_2 R_\odot = 8.7 \times 10^9 m_2^{0.91} \text{ cm}. \quad (19)$$

This radius is so small for any reasonable stellar mass m_2 that the only possibility is a low-mass white dwarf, whose mass–radius relation we can take as

$$R_2 \simeq 1 \times 10^9 (m_2/0.5)^{-1/3} \text{ cm}. \quad (20)$$

We see that equations (19) and (20) are compatible for

$$M_2 = 0.21 M_\odot, \quad (21)$$

while from equation (18) we find a self-consistently large current eccentricity

$$e_0 = 0.94. \quad (22)$$

The future evolution of the system is straightforward: as the white dwarf expands on mass loss and the eccentricity decreases, the mass-transfer rate will drop sharply (typically as $\sim M_2^5$, cf. the similar

evolution of very short-period CVs, e.g. King 1988). The system will transfer mass at ever-slowing rates almost indefinitely.

4 ORIGIN

An important consequence of the low value of M_2 is that the current mass-transfer time-scale is very short, i.e. $t_{\dot{M}} \sim M_2/(-\dot{M}_2) \sim 2000$ yr. That we are nevertheless able to observe such a brief event means that the rate of similar events must be very high. Together with the low SMBH mass, these facts strongly favour some kind of tidal capture event as the basic origin of this kind of system. It is also clear that the current mass $M_2 \simeq 0.21 M_\odot$ of the orbiting white dwarf is too low to be the straightforward outcome of single-star evolution. There are two obvious possibilities:

(a) The white dwarf began mass transfer with a ‘normal’ mass $M_2 \simeq 0.6 M_\odot$. It is easy to show (e.g. King 1988) that with mass–radius relation $R_2 \propto M_2$ the orbital period goes as $P \propto M_2^{-1}$, so the original period must have been only $\simeq 3$ h.

(b) The white dwarf was originally the core of a red giant. If it is still close to its mass at that epoch, the red giant would have had a radius $\sim 12 R_\odot$. If instead the current white dwarf has already transferred a large fraction of its original mass, the giant would have been much larger. In all cases the red giant envelope could have had a significant mass.

Case (b) is considerably more likely, as it allows the interpretation that the current system is the survivor of some kind of tidal capture of a red giant [whereas Case (a) requires an ‘aim’ of implausible accuracy]. Case (b) could have been triggered by a full tidal disruption event (TDE) involving explosive mass transfer, but a near-miss event in which the giant was captured into an orbit where it eventually lost mass only at pericentre (as the white dwarf does now) is more probable. The conditions for a full TDE are extremely restrictive, so the kind of near-miss event discussed here instead must be far more common. Mass transfer would have stopped for a time, once the giant lost its envelope. The binary separation at this point would have been noticeably wider ($a(1-e) \sim 7 \times 10^{13}$ cm for the minimum giant radius of $12 R_\odot$), but gravitational wave emission would have made the white dwarf core fill its tidal lobe on a relatively short time-scale, because of the high eccentricity.

5 IMPLICATIONS FOR SMBH FEEDING

I have argued above that tidal near-miss events like the one studied here must be quite common, suggesting that similar events with different infalling stars should also occur. But it seems likely that the particular event studied here was unusually favoured for observation, as one might expect, given that currently, it is fairly unique. The favouritism arises because the very small stellar radius, and hence very high mass density, means that mass transfer starts only at a rather small pericentre distance, where GR can drive very rapid mass transfer. It is a well-known result of Roche geometry (e.g. King 1988) that the mean mass density $\bar{\rho}$ of a lobe-filling star goes as P^{-2} , where P is the orbital period. This is aided still more in the present case because of the high eccentricity. More massive and therefore more extended infalling stars fill their Roche lobes at wider separations, corresponding to much longer orbital periods P . From equation (15), we see that the $P^{-8/3}$ dependence of the GR-driven mass-transfer rate is likely to outweigh the m_2^2 effect of an increased stellar mass.

This suggests that the present event may be only the most observable component of a considerably larger infall rate to the

SMBH. A similar – or even far greater – stellar infall rate in other galaxies would not be observable at all if the central SMBH is massive enough that the infalling stars are swallowed by the black hole before they fill their tidal lobes, which happens if $M \gtrsim 10^7 M_\odot$ (Kesden, 2012). At low redshift, we know from the Soltan (1982) relation that a mechanism like this cannot be supplying most of the largest SMBH masses. But it seems possible that it could be a significant contributor for small SMBH, and at higher redshift.

6 THE LIGHT CURVE

The eruptions characterizing the X-ray light curve of GSN 069 have far shorter time-scales than are likely for the usual diffusive viscous transport in accretion discs. They resemble the light curve of GRS 1915+105 (Belloni et al. 1997), which shows evidence for the viscous refilling of a disc depleted by flares. This kind of behaviour is modelled by King et al. (2004), who suggest that local dynamo processes can affect the evolution of an accretion disc by driving angular momentum loss in the form of an outflow (a wind or jet). The waiting time-scale for such eruptions to occur is much shorter if the disc is thick ($H \sim R$) as it is triggered by the chance alignment of local magnetic fields anchored in adjacent disc annuli, which has a time-scale $\sim 2^{R/H} t_{\text{dyn}}$, where t_{dyn} is the local disc dynamical time-scale $(R_g^3/GM)^{1/2}$. We will see below that there is a reason to expect a thick outer disc in this system.

The form of the X-ray light curve must also be strongly affected because the pericentre separation $p = (a(1-e_0) \simeq 6 \times 10^{11}$ cm is of the order of only $15R_g$. The standard formula

$$\Delta\phi \simeq \frac{6\pi GM}{c^2 a(1-e^2)} \quad (23)$$

for pericentre advance now gives

$$\frac{\Delta\phi}{2\pi} \simeq \frac{3R_g}{p} \simeq \frac{1}{5}, \quad (24)$$

so pericentre precesses one full revolution roughly every five orbits. If the inclination of the orbital plane to the line of sight is high enough, this may be detectable as a superorbital quasi-period $P_{\text{super}} \sim 2$ d in X-rays.

7 CONCLUSIONS

I have shown that the 9-h quasi-periodic X-ray eruptions from GSN 069 could result from mass overflow at pericentre from an orbiting low-mass star in a very eccentric orbit. I have argued that systems like this would result from near-miss TDEs, which should be considerably more common than genuine TDEs. Similar events involving more massive stars would be less observable. In combination with the very short lifetime of the current event, this suggests that stars fall close to the low-mass SMBH in this galaxy at a rate $\gtrsim 10^{-4} M_\odot \text{ yr}^{-1}$. A similar or even much greater inflow rate could have a major effect in growing SMBH masses, either at high redshift, or in growing low-mass SMBH at low redshift, but would be otherwise essentially unobservable.

This suggests several possible lines of future research. We have seen that the mass-transfer rate from any individual star falls very quickly below its initial value. Accordingly, the SMBH might on average be accreting from several of them at low rates simultaneously. Their orbital planes are presumably uncorrelated, making the outer disc thick, and so favouring the dynamo-driven outbursts discussed above. Numerical simulations might check this

picture, and see if the sudden periodic injections of mass when the star is at pericentre can trigger the eruptions.

Further X-ray observations of GSN 069 could potentially offer much more insight into this system, particularly, if the coverage is extensive enough to offer the chance of detecting the predicted superorbital modulation $P_{\text{super}} \simeq 2$ d. It is also clearly worthwhile, checking other galaxies known to have low-mass SMBHs for similar quasi-periodic eruptions.

A final point concerns the nature of the orbiting star: If this is the fully-stripped core of a red giant, the accreted material should be helium-rich. But it is possible that some of the envelope hydrogen may remain on the surface. At present, this question appears observationally intractable.

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