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SEARCHING FOR IR QPO IN THE GALACTIC CENTER BLACKHOLE CANDIDATE Sgr A*

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ABSTRACT

The compact, nonthermal radio source Sgr A* is believed to be a supermassive blackhole at the Galactic Center. Spectral and kinematic studies give confirming indications that its mass may be close to $10^6\ M_\odot$. Whereas most of the radio and high-energy emission appears to originate from within a quasi-spherical infall (extending out to $\sim 3 \times 10^{16}$ cm), the recently-detected IR luminosity is probably due to a small accretion disk (formed within $50 - 100$ Schwarzschild radii of the compact object), indicating that the inflowing plasma retains some angular momentum, forcing it to circularize before reaching the event horizon. The unequivocal identification of an accretion disk with a diameter $\sim 1 - 3$ AU would, of course, provide overwhelming evidence that the gravitational potential in this region is dominated by a point-like object, but we cannot yet entirely discount the possibility that the IR counterpart to Sgr A* is due to a chance coincidence with a faint star. However, only disk emission is known to exhibit Quasi-Periodic Oscillations (QPOs). We show that the expected amplitude ($\lesssim 20 - 40\%$) and frequency ($0.002 - 0.00014$ Hz) of QPOs in the IR spectral component of Sgr A* might be measurable with current IR imaging instrumentation, which could then provide the essential observational diagnostic to discriminate between the actual disk emission and the contribution from a contaminating foreground object.

Subject headings: blackholes—galaxies: the Galaxy—center: winds—QPO—stars: supergiants

1. Introduction

The importance of the compact, nonthermal radio source Sgr A* is underscored by its uniqueness, its low proper motion ($\lesssim 40$ km s^{-1}), and its location at or near the dynamical center of the galaxy, which together have led many to suggest that it may be a massive point-like object dominating the gravitational potential in the inner $\lesssim 0.5$ pc region (Lo 1987). The radiative emission from this black hole candidate may be due to accretion from a galactic center wind (Melia 1992a), whose existence is implied by the observation of broad He I, Brα, and Brγ emission lines from the vicinity of IRS 16 (Hall et al. 1982; Geballe et al. 1984; Allen et al. 1990), and of Ne^+ (Serabyn et al. 1991) and radio continuum (Yusef-Zadeh & Melia 1992) radiation from IRS 7, a class M2I supergiant located $\sim 3/4$ lyr to the north of Sgr A*. Once captured, with an accretion rate $\dot{M} \approx 1 \times 10^{22}\, {M_6}^2$ g s^{-1} (where M_6 is the black hole mass in units of $10^6\, M_\odot$), the inflowing gas structure is quasi-spherical, unless the plasma carries an unreasonably large specific angular momentum (i.e., $l \gg \lambda c r_g$, where $r_g \equiv 2GM/c^2$ is the Schwarzschild radius and $\lambda \approx 3 - 10$). Since this accretion rate is well below the value at which the outwardly propagating radiation field decelerates the flow, the accreting gas is essentially in radial free-fall starting at the "accretion" radius $\sim 10^5\, r_g \approx 3 \times 10^{16}\, M_6$ cm, and extending down to $\sim 50\, r_g$, or less. Dissipation in this "extended" flow can account very well for the radio and X-ray/γ-ray spectra observed in Sgr A*, but only for a black hole mass M in the approximate range $0.5 \times 10^6\, M_\odot \lesssim M \lesssim 2 \times 10^6\, M_\odot$, with the best fit value at $\approx 0.9 \times 10^6\, M_\odot$ (Melia 1992a).

However, the gas "circularizes" at a radius $r \approx 2\lambda^2\, r_g$, so that either an anisotropy in the ambient medium or a dynamic fluctuation in the accretion pattern, both of which can impart an excess angular momentum to the infalling gas, can lead to the formation of a small disk at $r \lesssim 50 - 100\, r_g$ (Melia 1992a, 1993). Indeed, there is some evidence that a large fraction of the 2.2 μm luminosity from the nucleus of M31 may in fact be due to such a disk surrounding a Sgr A*-like object in that region (Melia 1992b). More recent infra-red observations of our Galactic Center suggest that Sgr A* too may possess a small disk dominating the spectrum at intermediate frequencies (10^{13} Hz $\lesssim \nu \lesssim 10^{16}$ Hz). As

shown in Figure 1, a single value of M ($\approx 1 \times 10^6\ M_\odot$) can therefore reasonably fit the entire source spectrum across roughly 12 decades in frequency (see also Melia, Jokipii & Narayanan 1992).

In view of the fact that kinematic studies of the stellar cluster at the Galactic Center also suggest the presence of a similar-sized object (Rieke & Rieke 1988), this "spectral" evidence in favor of a massive black hole identification for Sgr A* is quite compelling. Nonetheless, one can not yet entirely discount the possibility that, at least in the IR band, the emission from the central region is contaminated by a chance coincidence with a faint star. An observational diagnostic to discriminate between disk and stellar emissions would therefore be invaluable. Since only disk emission is expected to show Quasiperiodic Oscillations (QPOs), the detection of these modulations, characterized by excursions in frequency and phase, would then argue strongly in favor of the black hole scenario elucidated above.

2. The Expected Frequency and Amplitude of the QPO

QPOs have been seen frequently in white dwarfs and neutron stars accreting from binary companions. It is believed that the intensity fluctuations are associated with unstable processes in a differentially rotating disk surrounding the central compact object, producing frequencies $\nu_{QPO} \sim 5 - 60$ Hz. More recently, QPOs have also been seen from several galactic black-hole candidates, such as Cygnus X-1 (Vikhlinin et al. 1992; Angelini, White & Stella 1992), though for these sources, ν_{QPO} is typically about 0.04 Hz, consistent with an orbital period at a radius $r_{QPO} \equiv (GM/4\pi^2\nu_{QPO}^2)^{1/3} \approx 580\, r_g$ for a blackhole mass $M = 10\, M_\odot$. Such a large value for r_{QPO} suggests, perhaps, that the instability giving rise to the QPOs affects the disk more globally than just in its inner region.

Although several earlier claims of periods or quasiperiods in Active Galactic Nuclei have not survived the test of time, observations of quasiperiodic variations (with a time scale of around 500 seconds) in the X-ray emission from the Seyfert galaxy NGC5548 (Papadakis & Lawrence 1993) and of the periodic ($\sim 12,100$ seconds) X-ray flaring in NGC6814 (Mittaz & Branduardi-Raymont 1989) appear to extend the QPO phenomenon

to much more massive systems. For example, the fluctuations in NGC6814 could be the result of disk modulations at a distance of $\approx 50\ r_g$ from a one million solar mass black hole. In addition, the QPOs seen in NGC5548 show a correlation of frequency and amplitude with source intensity that is reminiscent of those seen in the 'Z' low mass X-ray binaries (LMXBs) when on the horizontal branch of the X-ray colour-intensity diagram (van der Klis 1989). The QPO frequency increases with the source intensity, whereas the strength (fractional root mean square amplitude of the variability, or f.r.m.s.) decreases as the source brightens.

The QPO modulation could arise from one of several processes in the disk, all connected in one way or another to the orbital period. Bright spots on the accretion disk (Abramowicz et al. 1991), physical variations in a corona (Boyle et al. 1986; Melia & Zylstra 1992), and unstable flaring in a pair plasma (Moskalik & Sikora 1986) are particular examples. It is conceivable that more than one (perhaps most) of these mechanisms contribute to the QPO phenomenon, though the pair plasma model is unlikely to be relevant in the case of Sgr A* since the instability is expected to develop only in a narrow luminosity range when the γ-ray luminosity of the source is ~ 1 percent of the Eddington limit, much higher than is observed from the galactic center (see above).

The relative constancy of the spectral index with flux in sources such as NGC6814 argues against major changes in the disk structure, supporting instead the view that the variability is associated primarily with local perturbations that do not disrupt the overall system geometry. The expected amplitude of the QPO fluctuations depends principally on the size variations associated with the disk's surface of emission. It is now known (Blumenthal et al. 1984; Wallinder 1991) that standard α-disk models admit not only classical thermal and viscous instabilities, but also radial pulsational instabilities in both the gas and radiation pressure-dominated regions. At the particle densities implied by the accretion rate onto Sgr A* ($\dot{M} \approx 1 \times 10^{22}\ {M_6}^2$ g s^{-1}), the disk is optically thick, an inference supported by the best fit spectrum (at frequencies $10^{13} \lesssim \nu \lesssim 10^{17}$ Hz) shown in Figure 1. The disk flux is therefore given as $F = 2acT^4/3\kappa\Sigma$, where T is the mid-plane

temperature, Σ is the surface mass density, and κ is the radiative opacity, due mostly to Thomson scattering in the inner radiation pressure-dominated ($P_r \gg P_g$) and the intermediate gas pressure-dominated ($P_g \gg P_r$) regions of the disk. In the perturbation analysis of Blumenthal *et al.* (1984), all the fluctuations in the dynamical quantities, such as those of the angular frequency ($\delta\Omega$) and the temperature (δT), can be written in terms of $\delta\Sigma/\Sigma$. It is quite straightforward to show that the perturbed flux is given as $\delta F/F = \phi\ \delta\Sigma/\Sigma$, where $\phi \sim 1$. Thus, since $\delta\Sigma \sim \Lambda^2$, where Λ is the wavelength of the pulsational mode, we expect that $\delta F/F \approx \phi\,(2\pi/kr)^2$, where $k \equiv 2\pi/\Lambda$ is the wavenumber of the fluctuation.

In the inner ($P_r \gg P_g$) region, the disk is unstable to radial oscillations for a wide range of the viscosity parameter α ($\lesssim 1$) and $Q \equiv (kH)^2$ ($\lesssim 1$), where H ($\ll$ the radius r) is the scale height in the z-direction. In the intermediate region, the oscillatory mode instability dominates over the thermal and secular modes when $\Lambda \lesssim 15\ H$ (the short wavelength limit), and for all reasonable values (i.e., $\lesssim 1$) of α. The disk is apparently also unstable in the outer region (where $P_g \gg P_r$ and the opacity is dominated by free-free processes) as long as $Q \lesssim 1$ and $\alpha \gtrsim 0.1$. Here, smaller values of α damp the oscillations.

Although the exact value of H/r is uncertain, it probably lies in the range $0.01 \lesssim H/r \lesssim 0.1$, depending on how steady the viscosity α is. Thus, one can reasonably expect flux variations in the range $0.004 \lesssim \delta F/F \lesssim 0.4$, with the larger (smaller) value corresponding to a lesser (greater) condensation of the disk plasma toward the mid-plane. The available observational evidence suggests that the QPO amplitude can indeed cover this entire range. Several observations of NGC5548 have revealed that the f.r.m.s. value in this source ranges from $\sim 3\%$ to more than 8%, whereas EXOSAT observations of NGC6814 have identified X-ray flaring at the level of $\sim 30 - 60\%$ above the continuum (Mittaz & Branduardi-Raymont 1989).

QPO fluctuations in Sgr A* would be associated with a time scale that depends on the mass of the central object, and whether the dominant mode instability occurs in the inner or intermediate regions of the disk. Since the mass of Sgr A* is apparently $\approx 10^6\ M_\odot$ (see

above), we anticipate that the QPO period should range from ~ 8 minutes for a Keplerian orbit at $r_{QPO} \approx 3r_g$, to as much as ~ 2 hours if $r_{QPO} \approx 20r_g$.

3. Discussion

With ongoing technological developments in infrared imaging, fluctuations with amplitudes and time scales such as these might now be measurable. For example, the FASTTRAC infrared tip-tilt (adaptive optics) system developed by Close & McCarthy (Close & McCarthy 1993) should produce nearly diffraction limited images at K (0.2″ FWHM) on nights of sub-arcsecond seeing. Using the 6.7 mag (at K) guide star IRS 7, FASTTRAC has already produced the first adaptive optics images of the Galactic Center, with a detection of a point source (in both H and K bands) at the position of Sgr A* (Close et al. 1993). Thirty-second snapshots of this field should be able to identify intensity variations as low as $\sim 10-20\%$, and could therefore conceivably be used to track quasi-periodic oscillations in this source with the expected QPO period of 8 minutes or more.

To date, QPOs have been seen in the X-ray light curves of many LMXRBs, in the optical emission of dozens of dwarf novae during eruption (Patterson 1981), and in the radio flux from some of these objects (Gotthelf et al. 1991). A detection of IR QPOs in Sgr A* would add considerably to our QPO data base in a currently unexplored region of the spectrum. But much more importantly, it would demonstrate convincingly that the IR emission from the location of Sgr A* is associated with a nuclear accretion disk rather than a contaminant object, such as a foreground star. In this respect, a detection of QPO from Sgr A* would provide overwhelming evidence that the Galactic Center harbors a massive black hole.

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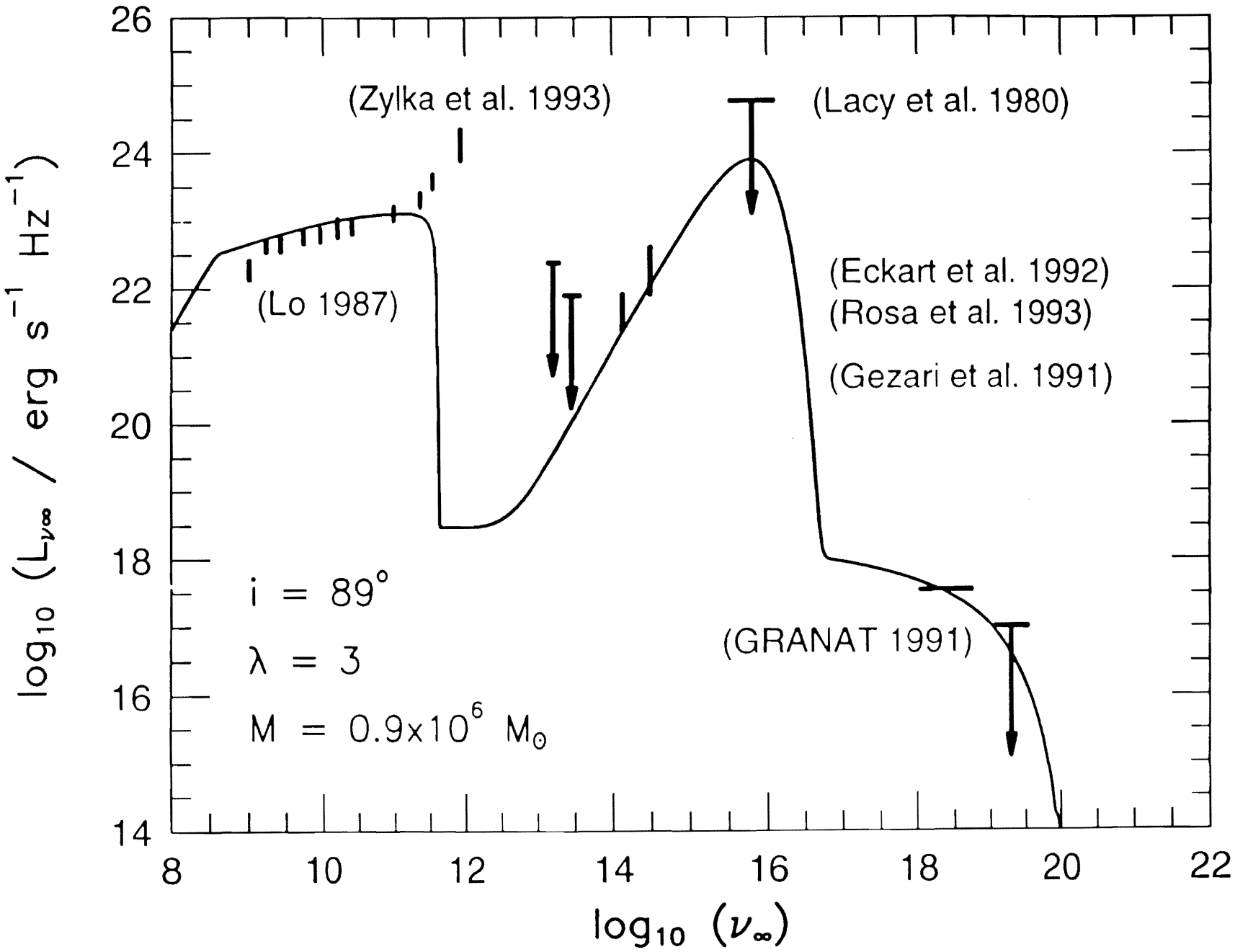
FIGURE CAPTION

Fig. 1. – The spectrum of the Galactic Center Blackhole candidate Sgr A*, assuming a source distance of 8.5 kpc. The data are taken from Lo (1987), Zylka et al. (1993), Lacy et al. (1980), Eckart et al. (1992), Rosa et al. (1993), and Gezari & Dwek (1991). The theoretical curve is based on the model discussed in Melia (1992a, 1992b, 1993) and Melia et al. (1992). The radio and X-ray emission is dominated by dissipational proceses in the extended, quasi-spherical infall (at $10^5\ r_g \gtrsim r \gtrsim 50\ r_g$), whereas the IR emission is presumably dominated by a small accretion disk with a high inclination. A single value of the mass M can account for the whole frequency range shown here. The turnup at $\nu \sim 100$ GHz is probably due to dust emission, which is opaque at $\lambda 1000\ \mu$m with a temperature of $T_{dust} \sim 60$ K (Zylka et al. 1993). The assumed value of the inclination angle affects only the disk emission. The luminosity from the extended flow depends principally on M, which then allows us to infer its value directly from the very low and very high frequency data.

Figure 1


(Zylka et al. 1993)
(Lacy et al. 1980)
(Lo 1987)
(Eckart et al. 1992)
(Rosa et al. 1993)
(Gezari et al. 1991)
(GRANAT 1991)
i = 89°
λ = 3
M = 0.9x10^6 M⊙
log10 (Lν∞ / erg s^-1 Hz^-1)
log10 (ν∞)
26
24
22
20
18
16
14
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