A NEW WAY TO DETECT MASSIVE BLACK HOLES IN GALAXIES: THE STELLAR REMNANTS OF TIDAL DISRUPTION

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ABSTRACT

We point out that the tidal disruption of a giant may leave a luminous (10^{35}–10^{39} ergs s^{-1}), hot (10–100 eV) stellar core. The "supersoft" source detected by *Chandra* at the center of M31 may be such a core; whether or not it is, the observations have shown that such a core is detectable, even in the center of a galaxy. We therefore explore the range of expected observational signatures and how they may be used to (1) test the hypothesis that the M31 source is a remnant of tidal stripping and (2) discover evidence of black holes and disruption events in other galaxies.

Subject headings: galaxies: individual (M31) — X-rays: stars

1. TIDAL DISRUPTION OF GIANTS: THE CORE REMAINS

A star of mass M_* and radius R_* can be tidally disrupted by approaching within R_t of a black hole (BH);

$$R_t = \left(\eta^2 \frac{M_{bh}}{M_*}\right)^{1/3} R_*,\tag{1}$$

where M_{bh} is the BH's mass and η is a parameter of order of unity. Let R_S be the BH's Schwarzschild radius. For $M_{bh} \gtrsim 10^8\, M_\odot$, $R_t < R_S$ for most main-sequence stars, and only tidal disruptions (TDs) of giants lead to observable effects. The rate of such TDs, $\dot{N}_G$, depends on M_{bh}, the kinematics of stars near the galactic nucleus, and the mass and age distribution of these stars (see, e.g., Magorrian & Tremaine 1999). Computed rates are typically in the range 10^{-6} to 10^{-4} yr^{-1}. A convenient expression is

$$\dot{N}_G \sim 10^{-5} \left(\frac{L}{L_*}\right)\ \text{yr}^{-1},\tag{2}$$

with $L_* = 1.8 \times 10^{10}\, L_\odot$; this was derived by Syer & Ulmer (1999), who also provide cautions about the use of a simple scaling law. Studies of TD have focused on possible associated accretion events, lasting for months or decades, with luminosities as high as $\sim 10^{44}$–10^{46} ergs s^{-1} (see, e.g., Hills 1975; Lidskii & Ozernoi 1979; Gurzadyan & Ozernoi 1980; Rees 1988; Loeb & Ulmer 1997; Ulmer, Paczyński, & Goodman 1998; Ulmer 1999).

The hot core of a disrupted giant.—The disruption leaves an end product, the giant's hot dense core, whose presence, influence, and observability are the subjects of this paper. The core remains hot ($T > 10^5$ K) and bright ($L > 10^2\, L_\odot$) for 10^3–10^6 yr, thereby providing the longest lasting signal of a TD.

Detectability.—The soft X-ray sensitivities of *Einstein*, *ROSAT*, *Chandra*, and *XMM-Newton* have allowed them to detect supersoft X-ray sources (SSSs) in other galaxies. SSSs

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(Greiner, Hasinger, & Kahabka 1991; Rappaport, Di Stefano, & Smith 1994; Kahabka & van den Heuvel 1997) have luminosities (10^{35}–10^{38} ergs s^{-1}) and temperatures ($kT \sim 10$–100 eV) comparable to those of hot stellar cores. *Chandra*'s $0\farcs5$–$1''$ angular resolution allows individual sources to be resolved, even in the dense central regions of nearby galaxies.

The example of M31.—We have studied 8.8 ks of data collected by *Chandra*'s ACIS-I detector. To identify SSSs we applied a hardness ratio test to all point sources in a $16' \times 16'$ region centered on the center of M31, selecting all sources with more than 50% of their photons below 0.7 keV. Three sources satisfied this condition. Remarkably, one of these is coincident with the center of M31. The luminosity is $\sim 10^{37}$ ergs s^{-1}; the data are consistent with little or no emission above 1.5 keV. The source appears to be variable; data from earlier missions (*Einstein*, *ROSAT*), e.g., are consistent with the source providing zero flux on one occasion. Garcia et al. (2000) have argued that the density of point X-ray sources in this field is so low that a chance coincidence with the center is highly unlikely; this argument is even stronger when applied to SSSs. The observed SSS-like behavior is therefore most likely related to the environment of the center, presumably to the presence of a massive black hole (MBH). The data do not seem consistent with advection-dominated accretion flow disk models (see, e.g., Garcia et al. 2000) but are compatible with the signature of a hot stellar core. Whether or not the source is a hot core, the M31 observations establish that it is possible to detect such an object in the centers of nearby galaxies.

2. THE NATURE OF THE CORES

The nature and characteristics of the core depend on the initial mass, M_*, of the stripped star and on its state of evolution at the time of disruption.

2.1. $M_* < 8\, M_\odot$

Tidal stripping brings a premature halt to nuclear burning. While any residual nuclear burning continues, the luminosity remains at the value it had when the star was a giant. The radius shrinks, and the effective temperature increases. Depending on the core mass, these systems will stay at $L > 10^2\, L_\odot$ and $T > 10^5$ K for 10^3–10^5 yr (see, e.g., Blöcker 1995; Gorny, Tylenda, & Szczerba 1994).

Nature has provided direct analogs, in the form of the hot cores at the centers of planetary nebulae. A notable example

is 1E 0056.8−7154, a planetary nebula system in the Small Magellanic Cloud, with $L = 2 \times 10^{37}$ ergs s^{-1} and $kT =$ 30–40 eV (Wang & Wu 1992).

The evolution of the hot core is influenced by its mass, its state at the time of disruption (e.g., its thermal pulse-cycle phase), and the mass of the original star (see, e.g., Iben 1995 and references therein). The hot core of a star that was disrupted at some arbitrary time in its evolution is descended from a more massive star than a core of the same mass emerging during the final stages of an uninterrupted evolution. The core of the disrupted star is therefore younger and is generally less compact, with a significantly higher core temperature; it cools more slowly than typical post–asymptotic giant branch (AGB) stars. (See, e.g., Blöcker 1995; Gorny et al. 1994.) Although these results were arrived at by studying winds, they are expected to be valid for the extreme mass-loss scenario associated with disruption.

The stellar mass function favors stars in this mass range, and they are therefore expected to be disrupted more frequently than stars of higher mass. Nevertheless, we go on to consider high-mass stars, because their disruption may also produce remnants with observable signatures.

2.2. $M_* > 8 \, M_\odot$

The stripped core is a helium star (He star). Two processes (in addition to TD) may produce He stars. First, a very massive star may eject such copious winds that it effectively ejects its own hydrogen envelope. Second, a massive star in a binary may overfill its Roche lobe as it evolves and lose its hydrogen envelope by either transferring it to its companion (if the mass ratio is not too extreme) or losing it during a common-envelope episode. The evolution of isolated He stars and He stars in binaries has been well studied; see, e.g., Maeder (1981), Delgado & Thomas (1981), Habets (1986, 1987), de Loore & De Greve (1992), Reese (1993), and Woosley, Langer, & Weaver (1995). The characteristics of each stage of the He star's evolution depend on many factors, including the mass of the star when its envelope was lost and the continuing rate of mass loss to winds. A common feature of these evolutions is, however, that, for a wide range of system parameters, there is a time interval lasting up to several million years, during which the star is both very luminous (10^{38}–10^{39} ergs s^{-1}) and very hot, with kT near 10 eV. Characteristic evolutionary sequences include an epoch of helium burning, a shorter epoch during which heavier elements are burned, and, in some cases, a Type Ib or Type Ic, hydrogen-poor supernova.

Typical temperatures are lower and typical luminosities higher than those considered in § 2.1. Another distinction is that the core may not be hottest and brightest immediately after the TD. This is because the further evolution of the He star will typically increase its luminosity and alter its temperature; in addition, winds that can block emergent soft X-rays tend to decrease with time.

Wolf-Rayet stars may be the closest well-observed analogs of the He-star remnants of TDs. They tend to eject such significant winds, however, that their appearance may be dominated by the interaction of this surrounding matter with radiation from the He star. Perhaps because of this, no known He star has a "supersoft" signature. It is possible, however, that some of the known SSSs, whose fundamental nature is not yet understood, could be He stars.

He-star remnants of TDs may be more likely than other He stars to be observed as SSSs. This is because the BH continues to act as a sort of vacuum cleaner for mass outside the tidal radius [$\sim R_t(M_*/M_{bh})^{1/3}$]. Furthermore, since self-generated winds tend to decrease with time (see, e.g., Woosley et al. 1995), there will typically be less and less material within the tidal radius, even as nuclear evolution continues. Thus, He stars near MBHs, especially those that have undergone TD, may provide the cleanest signatures of the underlying properties of the star, distinct from the signatures of its interactions with its environment.

3. OBSERVATIONAL SIGNATURES

Luminosity.—For both white dwarfs and He stars, the luminosity of the stripped core should not exceed that of typical giant stars. Luminosities in excess of $\sim 10^{39}$ ergs s^{-1} must be due to some alternative or additional effect.

Spectrum.—The maximum temperature expected for hot white dwarfs (He stars) is ~ 100 (15) eV. Therefore, when N_H is low, the X-ray spectrum is dominated by soft photons. There can also be a modest contribution from photons at higher energies. First, the spectrum could differ from a simple thermal shape, e.g., because of opacity effects, as is well known in the case of white dwarf atmospheres (see, e.g., Dupree & Raymond 1983; van Teeseling, Heise, & Paerels 1994; Hartmann & Heise 1997); thus, atmospheric effects must be included when fitting the X-ray spectrum. Second, there could be contributions from a corona, an infall disk within the stellar core's Roche lobe, or shock heating of the ambient medium. Finally, it may not be possible to resolve the hot core and the MBH, which should be accreting matter at a low level, e.g., from stellar winds. Note that any radio emission is more likely to be originating from the region around the MBH than from the hot remnant of TD.

It is important to look for distinctions between the signature of tidally stripped remnants and other possible explanations for SSS signatures. One distinction, e.g., between SSSs in binaries and stripped cores, should be that the distinctive disk signatures of the former (Popham & Di Stefano 1996) should be missing in the latter.

Ionization.—Even if the total flux from a stripped core over its lifetime (which, for the purposes of ionization signatures, may be defined to be the time interval during which $T >$ 50,000 K) is smaller than that from the accretion flare event, the number of high-energy ionizing photons it emits may be significantly larger. The distinctive signature is photoionization of high-energy states.

Time variability.—Intrinsic variability may occur at many timescales. Here we concentrate on variability due to absorption of soft X-radiation by a varying amount of matter lying between the source and our detectors. Figure 1 demonstrates that the decline in count rate with increasing column density can be dramatic.

If the stripped core orbits the MBH, the flux we receive may decrease as it travels behind gas in the disk around the MBH. If the mass and radius of the star were M_* and R_* before the TD and if the orbital separation between the core and the MBH is presently equal to the separation at which the star filled its Roche lobe, then

$$P_{\rm orb} = 0.32 \text{ yr } \eta \left(\frac{R_*}{100 \, R_\odot}\right)^{3/2} \left(\frac{M_\odot}{M_*}\right)^{1/2}. \qquad (3)$$

If the core escapes from the vicinity of the MBH, it could also exhibit variability as it passes behind gas clouds. Making a set of simple assumptions, we estimate the amount of time,
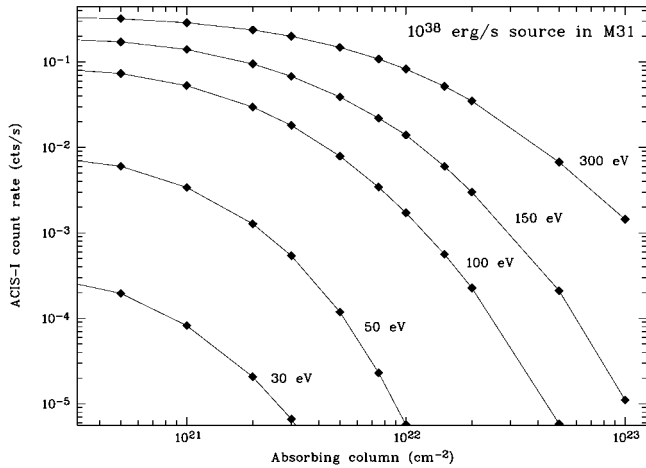
FIG. 1.—*Chandra* ACIS-I detector count rates of a blackbody radiator with a bolometric luminosity of 10^{38} ergs s^{-1} in M31 for different temperatures (*solid lines*) and depending on the intervening absorbing column.

τ, it takes for the hot core to pass behind a cloud with column density N_H, located a distance a from the massive black hole;[4]

$$\tau = \frac{3.5 \text{ days}}{v_{150}} \xi \left(\frac{N_H}{N_{H,O}}\right)\left(\frac{a}{pc}\right)^3 \left(\frac{3 \times 10^7 \, M_\odot}{M_{bh}}\right), \quad (4)$$

where ξ is of order unity, v_{150} is the transverse speed in units of 150 km s^{-1}, and $N_{H,O} = 1.9 \times 10^{22}$. The actual duration of obscuration may be shorter or longer, depending on the geometry of the cloud and the track of the hot remnant.

Doppler shift.—The orbital speed of the star in a circular orbit around a $3 \times 10^7 \, M_\odot$ black hole, with orbital separation, a, such that a 100 $R_\odot$ star fills its Roche lobe, is ~5%c; the speed of the hot remnant could be greater. Thus, the most direct confirmation that an observed SSS is a tidally stripped remnant would be a periodic Doppler shift compatible with an orbit small enough to allow TD of the progenitor star. Significant blue- or redshifts could possibly be inferred from spectral fits. Even if the remnant does not orbit the MBH, it might be possible to measure its velocity and establish the likelihood that it is escaping from the central gravitational potential.

Spatial distribution.—If the hot stellar core escapes from the region around the MBH, traveling along a direction perpendicular to our line of sight, it could traverse a considerable distance before it dims and cools. If the average speed is ~10^8 cm s^{-1}, the core could travel ~1 (0.1) kpc in 10^6 (10^5) yr. If the product of the TD rate and average hot-core lifetimes is larger than unity, we might expect to see several hot cores ringing the MBH, with the oldest cores farther away. Any cores located ~1 kpc from the galaxy center would likely be He stars. It is interesting to note that the other two SSS candidates near the center of M31 are each several arcminutes from the galaxy's center, produce count rates similar to that of the central SSS, and are each considerably softer than the central source.

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[4] Consider a cloud with mass m located a distance a from the MBH. If the cloud is corotating, the largest volume it could have is roughly equal to the volume of a sphere whose radius is the effective Roche lobe radius. This allows us to relate the mass of the cloud to its radius R, its distance a from the MBH, and to M_{bh}. Assume the cloud is composed of hydrogen and that we can approximate an average value of N_H by the number of hydrogen atoms divided by the square of the cloud radius. This allows us to relate R to N_H. Finally, we use $\tau = R/v$.

Population signatures: 1. Consistency with the model.—If N M31's SSSs are remnants of TD events, each represents a much larger population of giants in the galaxy's central region at the time of the TD. We must therefore test whether the present-day population could have evolved from one with the requisite number of giants some 10^3–10^6 yr ago. If we determine that a subset of the TD remnants are He stars, it is likely that there were a large enough number of centrally located high-mass stars active in the recent past to lead to some supernovae. We can ask whether the characteristics of the central region (up to ~1 kpc from the center) are consistent with the required number of Type II or Type Ib and Ic supernovae. The degree and characteristics of the ionization of the central region must also be consistent with the effects expected from the N TD remnants and the requisite total population of high-mass stars. It may be instructive to consider the population of He stars near the center of the Milky Way, which is much better studied. This population is large and includes members with apparently unusual properties. (See, e.g., Tamblyn et al. 1996; Najarro et al. 1994 and references therein.) Unfortunately, the large column density toward the center of the Milky Way makes it impossible to study any soft X-ray emission from these stars.

Population signatures: 2. Eliminating other possibilities.—Population studies of the region around the galactic center can lead to estimates of the numbers of post-AGB stars and also of X-ray binaries of various types. The physical processes that give rise to each of these objects also may give rise to SSSs that have nothing to do with TD. We therefore need (1) observations of the central population, (2) theoretical estimates of the number of SSSs not due to TD expected, and (3) comparisons with studies of populations located away from the central region. These should allow us to estimate the probability that soft sources observed near the center have their genesis through processes that are ordinary and expected parts of stellar and binary evolution.

4. OTHER GALAXIES

Radiation from a hot stripped core can be detected in other galaxies if (1) the count rate is high enough and (2) the source can be resolved.

Count rate.—The count rate from the soft X-ray source in the center of M31 (Garcia et al. 2000) was ~10 counts ks^{-1}. Based on spectral fits to nearby (brighter) sources, the absorption was estimated to be $(2.8 \pm 1.0) \times 10^{21}$ cm^{-2}. The number of counts expected from an E kilosecond exposure of a source with similar spectrum, located a distance D from us, is approximately

$$N_\gamma = 10 \text{ counts} \times E \times \left(\frac{\text{Mpc}}{D}\right)^2 \times f\left(\frac{N_H}{2.8 \times 10^{21}}\right). \quad (5)$$

N_H is the column density between us and the new source. For face-on or early-type galaxies, N_H could be smaller than 2.8×10^{21}, increasing the count rate in a way that depends on the spectrum but that is likely to be described by a nonlinear monotonically decreasing function, $f(N_H/2.8 \times 10^{21})$. (See Fig. 1.)

A 50 ks exposure could therefore yield 20 counts from a hot stellar core an in M31-like galaxy as far away as 5 Mpc; for galaxies with less internal absorption, the count rate would be higher. Should the photons' energies be clustered below 1 keV, we would have convincing evidence for a centrally located soft X-ray source. *XMM-Newton*, with its higher effective area, could

achieve similar numbers of counts for galaxies up to 10 Mpc away. There are about 200 (600) galaxies within 5 (10) Mpc listed in SIMBAD and the Principal Galaxies Catalog. The galaxy type or orientation could allow the detection of soft central X-ray sources in roughly one-third of these galaxies.

Spatial resolution.—In M31 there are four other X-ray sources within ~10″ of the nucleus. If the central density of X-ray sources in other galaxies is similar, we might not be able to resolve the central source in galaxies farther from us than 2–3 Mpc. Note, however, that, if the soft central source is variable, as the source in M31 appears to be, it may be possible to apply successfully to X-ray searches for central sources the same difference imaging techniques that have been applied to optical searches for supernovae and microlensing. If the hard X-radiation is steady or varies in a way well known from studying other X-ray stars, then we may be able to infer the existence of the soft central source. *XMM-Newton*, which has 4–5 times *Chandra*'s effective area at low energies, will make such differencing studies possible for M31-type galaxies at least as far away as 5 Mpc. This is particularly so if simultaneous observations with *Chandra* can resolve some sources and help to determine their spectral characteristics.

Statistical tests.—Statistical questions can be posed when we study a population of galaxies. For example, are galaxies for which there is good evidence (perhaps from dynamical studies) for an MBH more likely to house a centrally located population of soft X-ray sources than galaxies for which the dynamical studies do *not* indicate the presence of an MBH?

5. CONCLUSION

When a giant is tidally disrupted, the stripped core may provide a hot and bright signature for 10^3–10^6 yr. Detecting such cores and relating them to TD events is challenging. Fortunately, the present generation of instruments, including *Chandra*, *XMM-Newton*, and the *Hubble Space Telescope*, promise opportunities for progress.

This new method of studying MBHs complements searches for flare events that may be due to TDs. The latter must of course be used for distant galaxies, and there is a growing body of evidence for luminous UV and X-ray events lasting for months to years, which may be consistent with the accretion of the envelopes of tidally disrupted stars.[5] Such events are so rare, however, that we would be lucky to detect one in the near future among the small number of galaxies within 5 or 10 Mpc. In nearby galaxies, however, the long-lived signatures of the stripped cores may allow us to infer that TDs have occurred. The two complementary modes of study should help us to understand better the frequency and consequences of tidal disruption events and to use them as probes of massive black holes in the centers of galaxies.

[5] Examples: the UV flare in NGC 4552 (Renzini et al. 1995), the ~5 × 10^{43} ergs s^{-1} outburst in IC 3599 (Brandt, Pounds, & Fink 1995; Grupe et al. 1995), the ~2 × 10^{43} ergs s^{-1} outburst in NGC 5905 (Bade, Komossa, & Dahlem 1996; Komossa & Bade 1999), the greater than 9 × 10^{43} ergs s^{-1} flare in RX J1242.6−1119 (Komossa & Greiner 1999), the ~10^{44} ergs s^{-1} flare in RX J1624.9+7554 (Grupe, Thomas, & Leighly 1999), the ~10^{44} ergs s^{-1} flare in RX J1331.9−3243 (Reiprich & Greiner 2001), or the ~2 × 10^{44} ergs s^{-1} flare in RX J1420.4+5334 (Greiner et al. 2000).

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