Ten Facts of Life for Distant Supersoft Sources

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Abstract

First discovered in the Magellanic Clouds and in the Milky Way, the largest pools of luminous supersoft X-ray sources (SSSs) now known lie in M31 and in more distant galaxies. Hundreds of newly-discovered SSSs are helping us to test models for Type Ia supernovae and to identify SSSs that may represent a wider range of physical systems, including accreting intermediate-mass black holes. In this short report we list ten intriguing facts about distant SSSs.

\textit{Key words:} X-ray sources; supersoft sources: galaxies; Type Ia supernova; symbiotic binaries, supernova remnants; intermediate-mass black holes

1 Introduction

Luminous supersoft X-ray sources (SSSs) were discovered and defined in terms of properties observed in a small number of sources ($\sim$ 18) in the Galaxy and Magellanic Clouds (MCs). Specifically, SSSs are defined in terms of their estimated luminosities ($L > 10^{36}$ erg s\(^{-1}\)) and their broad band spectra, with little or no emission above 1 keV. The physical nature of SSSs is not yet determined. In fact, the studies we summarize below indicate that they are likely to be a diverse group, with several different types of physical systems observable as SSSs, including white dwarfs (WDs), neutron stars (NSs), and black holes (BHs). Perhaps this diversity is to be expected, given the simplicity of the definition.

SSS effective radii are comparable to those of WDs. Indeed, roughly half of the SSSs in the MCs and Milky Way with optical IDs have counterparts that are consistent with systems known to contain hot WDs: planetary nebulae, recent novae, and symbiotic binaries (Greiner 2000). The remaining SSSs in the Galaxy and MCs have measured periods ranging from a few hours to a few days. The first and best-known model for these binary was developed by Ed van den Heuvel and collaborators (1992). The close-binary supersoft (CBSS) model, postulates that the...
prodigious luminosities are generated through the nuclear burning of material accreted by a WD. In order for nuclear burning to occur, the accretion rates must be high (close to or larger than $10^{-7} M_\odot$ year$^{-1}$). These high rates can be sustained only if the donor star is somewhat more massive than the WD and/or slightly evolved. An interesting characteristic of these models is that they allow the WD to increase its mass. Some SSS binaries may therefore be progenitors of Type Ia supernovae (Rappaport, Di Stefano, & Smith 1994; Di Stefano 1996; Kahabka & van den Heuvel 1997 and references therein).

While indirect evidence mounts that the WD model applies to some SSSs in the Galaxy and MCs, definite confirmation has been difficult. (See the contribution of Phil Charles to this volume.) One way to learn more about SSSs is to find them in other galaxies. We expect $\sim 1000$ SSSs to reside in spiral galaxies such as M31. (See Di Stefano & Rappaport 1994, Rappaport, Di Stefano, & Smith 1994, Yungelson et al. 1996.) Thanks to Chandra and XMM-Newton we have begun to study SSSs in distant galaxies. Below we list some of the things we have learned.

2 Ten Facts of Life

1. There is an extension of the class of SSSs to sources of somewhat higher energies. If SSSs are nuclear-burning WDs, the hottest systems would be those with masses near the Chandrasekhar limit, $M_C$; these could be as hot as 150 eV, with luminosities a few times $10^{38}$ erg s$^{-1}$. Particularly if such a hot WD lies behind a large absorbing column, its spectrum will appear to be harder than the spectra of most SSSs. Because of their potential physical importance, we must include any such sources when selecting SSSs from among the X-ray sources detected in external galaxies. By creating a selection procedure sensitive to hot SSSs, we discovered that there are sources with luminosities comparable to those of SSSs ($> 10^{36}$ erg s$^{-1}$), but with effective temperatures that can be significantly higher, generally between 100 eV and 350 eV. We refer to these somewhat hotter sources as quasisoft sources (QSSs). Several distant QSSs are bright enough to allow spectral fits; many of these are genuinely harder than the SSSs of the Galaxy and MCs. Many are variable, and are therefore more likely to be X-ray binaries than supernova remnants (SNRs). Although QSSs are almost certain to inhabit our own Galaxy and the Magellanic Clouds, this class has not yet been studied locally, and we do not know what they are. To summarize, we reserve the monicker SSS for sources with the characteristics of the “classical” SSSs (Greiner 2000), while QSSs are harder, but have little or no emission above 2 keV. We refer to any source that is either an SSS or a QSS as a very soft source, a VSS.

2. SSSs and QSSs are found in the bulges of spiral galaxies. High Galactic absorption prevents us from detecting SSSs in the Bulge of the
Milky Way. *Chandra*, however, has discovered eight SSSs in the bulge of M31 that would satisfy the standard criteria used to select SSSs (little or no emission above roughly 1 keV). There are also several QSSs. (See Di Stefano et al. 2004, and Orio 2005 for additional recent results from *XMM-Newton.*) SSSs and QSSs are also found in the bulges of other spiral galaxies (Di Stefano & Kong 2003, 2004, and Di Stefano et al. 2003).

3. **VSSs are found very close to the nuclei of both Local Group galaxies that house supermassive black holes.**

An SSS lies within 2″ of the central BH in M32 (Ho et al. 2003). A QSS lies within 2″ of the central BH in M31 (Garcia et al. 2000). Given the local spatial densities of VSSs in these galaxies, the probability that the projected position of a soft source is within a few parsecs of the nucleus is very low. It therefore seems likely that these sources are somehow related to the presence of the supermassive BHs. A natural explanation is that the sources are the hot cores of giants that were tidally stripped by the massive central BH (Di Stefano et al. 2001). In fact, if tidal disruptions of stars near supermassive BHs do occur, they should give rise to bright flare events. The hot cores of stripped giants would be the necessary complements. There are other possibilities. For example, the centrally located VSSs may be interacting binaries that were formed via stellar interactions in the high-density galactic bulge. Alternatively, the VSSs could contain intermediate-mass black holes (IMBHs) that have migrated toward the galaxy’s center.

4. **SSSs are found in elliptical galaxies and in globular clusters.** *Chandra* observations have discovered SSSs in elliptical galaxies (See Table 1; Sarazin, Irwin, & Bregman 2001; Di Stefano & Kong 2003, 2004), and in the GCs of NGC 4472 and M104. The evolutionary scenario for CBSSs suggest that SSS binaries should be present in elliptical galaxies. Novae and symbiotics are also expected to be found in old stellar populations.

5. **A large fraction of SSSs in spiral galaxies are associated with the spiral arms.** This suggests that many SSSs in spirals are younger than roughly 10⁸ years old. It seems unlikely that the majority of these systems are examples of close-binary supersoft sources, because the typical donor in a CBSS is a slightly evolved star with a mass of 1 – 2.5 M☉. Such stars are most likely to be found away from spiral arms and regions of star formation, because their ages are greater than 10⁸ – 10⁹ years. SSSs in the spiral arms could therefore be examples of different mass transfer scenarios, or they could be binaries with neutron star or black hole accretors.

6. **Two of the most luminous X-ray sources ever discovered are SSSs.** These may be good candidates for accreting intermediate-mass black holes (IMBH). In its high soft state, M101 ULX-1 is an SSS, with luminosity that has been observed to reach \( \sim 10^{41} \) erg s⁻¹. It
| Name   | Type | Chandra exposure (ks) | Total VSS | SSS | QSS | Canonical |
|--------|------|-----------------------|-----------|-----|-----|-----------|
| M101   | Sc   | 94.4                  | 118       | 53  | 32  | 21        | 65        |
| M83    | Sc   | 49.5                  | 128       | 54  | 28  | 26        | 74        |
| M51    | Sc   | 28.6                  | 92        | 36  | 15  | 21        | 56        |
| M104   | Sa   | 18.5                  | 122       | 22  | 5   | 17        | 100       |
| NGC 4697 | E   | 39.3                  | 91        | 19  | 4   | 15        | 72        |
| NGC 4472 | E   | 34.4                  | 211       | 27  | 5   | 22        | 184       |

Notes—Both SSSs and QSSs have been found in every galaxy studied to date. The examples in this table illustrate that VSSs constitute a smaller fraction of all X-ray sources in galaxies dominated by older stellar populations. Furthermore, in older populations the fraction of VSSs that are SSSs also tends to be smaller.

has also been observed as a QSS and, in its lowest observed state, as a hard X-ray source (Kong & Di Stefano 2005). The high-state luminosity is incompatible with the WD model, and may indicate that the accretor is a black hole with mass larger than $10 M_\odot$. In fact, if the soft component of the X-ray spectrum is emitted by the inner region of a multicolor disk, the inner disk radius is compatible with $\sim 1000 M_\odot$ BH. The state changes are also compatible with a BH accretor. (See also Fabbiano et al. 2003.)

7. Most SSSs are highly time variable. Time variability is a common characteristic of X-ray binaries. SSSs are no exception. Many are transient and some have been observed to vary within a single observation (see, e.g., Swartz et al. 2002). The number of transients and the observed on/off patterns are inconsistent with the hypothesis that the transients are dominated by recent novae.

8. Some SSSs are supernova remnants (SNRs). In M31 contains an X-ray resolved SSS with a counterpart detected in a narrow-band H$_\alpha$ image (Kong et al. 2003). Such a system raises the question of whether the SSSs we find in spiral arms may also be SNRs. This question can be resolved by taking multiple images. In fact, as discussed above, SSSs tend to be highly time variable, while SNRs cannot vary significantly over short times. Although a definitive study has not yet been carried out, the prevalence of variability, and the small fraction of SNRs in the Local Group that are SSSs conspire to make it seem unlikely that most spiral-arm SSSs are SNRs.

9. Link to Type Ia Supernovae:
If an accreting WD is to experience a Type Ia explosion, it must be able to retain the matter it accretes. The nuclear burning of accreted matter makes such retention possible, and this is the reason that SSS-like behavior is expected for accreting WD (single degenerate) progenitors of Type Ia supernovae. In spiral galaxies, the rate of SNe Ia is roughly $0.3 \text{ per century per } 10^{10} L_\odot$ in blue luminosity. If a typical progenitor WD must gain roughly $0.2 M_\odot$ in order for an explosion occur, and if the rate of mass accretion is $4 \times 10^{-7} M_\odot \text{ yr}^{-1}$, then a galaxy such as M31 or M101 should contain roughly 1000 SSSs that are Type Ia progenitors. This is roughly consistent with previous estimates of the total population of SSSs in spiral galaxies. There is a problem, however, since the accreting WDs which are Type Ia progenitors should tend to have the highest WD masses among the accretors, and to therefore be among the brightest, hottest, and most detectable SSSs. In fact, we can already rule out the possibility that most Type Ia progenitors in M31 and M101 are detectable as SSSs. This is so both for models in which the WD needs to achieve the Chandrasekhar mass in order to explode and for a range of sub-Chandrasekhar models. (See Di Stefano 2006 for details.) This result does not eliminate single degenerate models from consideration as possible Type Ia progenitors. It does, however, indicate that, if a significant fraction of Type Ia progenitors are accreting WDs, then they must be internally obscured. In fact, this is consistent with initial calculations for Type Ia progenitor models, and may be an indication that high rates of accretion are, as the calculations indicate, often accompanied by high rates of mass ejection. The ejected mass can then absorb soft radiation from the system.

10. QSS Models: Just as the type of X-ray emission that defines SSSs is associated with different types of physical systems, QSS-like behavior is likely to be exhibited by a variety of systems. Some QSSs may be SNRs, but variable QSSs are more likely to be X-ray binaries. One of the M31 QSSs which happens to be only slightly harder than a typical SSS has been tentatively identified as a symbiotic (Di Stefano et al. 2004b). Just as QSS broadband spectra are extensions of SSS spectra from 1 to 2 keV, it seems likely that QSS physical systems may represent extensions of those observed as SSSs. It could be, e.g., that some of the soft emission is reprocessed, with a fraction of it re-emitted at slightly higher energies.

3 Summary

When Ed and his collaborators carried out the first theoretical investigations of the newly established class of SSSs, it was clear that something exciting was going on. Fifteen years later, the study of SSSs in other galaxies is leading to new and unexpected discoveries and challenges. As we begin to develop a statistical sample of SSSs, we are finding that they are a diverse group, and that there are other soft sources, QSSs, that may be related to them. The realms of astrophysics associated with SSSs and QSSs span supermassive BHs, intermediate-mass BHs, X-ray bina-
ries with stellar-remnant accretors, Type Ia progenitors, and supernova remnants. If, fifteen years hence, we have succeeded in establishing the nature of the sources we detect, and developing theoretical constructs to describe them and the roles they play in the universe, we will have accomplished a good deal.

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