Harvard-Smithsonian Center for Astrophysics

Preprint Series

No. 4159

(Received September 5, 1995)

ON THE NATURE, POPULATION, AND IMPLICATIONS OF LUMINOUS SUPERSOFT X-RAY SOURCES

R. DiStefano

Harvard-Smithsonian Center for Astrophysics

and

S. Rappaport

Department of Physics and Center for Space Research
Massachusetts Institute of Technology

To appear in
The Proceedings of the 17th Texas Symposium

HARVARD COLLEGE OBSERVATORY

SMITHSONIAN ASTROPHYSICAL OBSERVATORY

60 Garden Street, Cambridge, Massachusetts 02138

Center for Astrophysics
Preprint Series No. 4159

**ON THE NATURE, POPULATION, AND IMPLICATIONS OF
LUMINOUS SUPERSOFT X-RAY SOURCES**

R. DiStefano
Harvard-Smithsonian Center for Astrophysics

and

S. Rappaport
Department of Physics and Center for Space Research
Massachusetts Institute of Technology

ON THE NATURE, POPULATION, AND IMPLICATIONS OF LUMINOUS SUPERSOFT X-RAY SOURCES

R. DISTEFANO

Harvard-Smithsonian Center for Astrophysics
Cambridge, MA 02138

S. RAPPAPORT

Department of Physics and Center for Space Research, MIT
Cambridge, MA 02139

OVERVIEW

The discovery of a new class of object suggests three central questions: What is the physical nature of the objects? How many of them are there? What are the implications of the existence of this population?

THE NATURE OF THE SOURCES

An important clue to the possible nature of the sources is that the spectra measured by ROSAT seem to be thermal, so that the relationship between the inferred temperature (typically tens of eV) and the inferred bolometric luminosity (typically $10^{37} - 10^{38}$ ergs s⁻¹) leads to the derivation of a characteristic size on the order of that of a white dwarf. Indeed, soon after it became clear that ROSAT was on the trail of a new class of source, the elements of a white dwarf accretor model were outlined in a paper by van den Heuvel, Bhattacharya, Nomoto & Rappaport¹ (hereafter vdHBNR). The critical observation of vdHBNR was that for mass transfer rates in the range of $\sim 1 - 4 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, hydrogen accreted onto the surface of a C-O white dwarf can be steadily burned and can provide luminosities in the range observed for supersoft sources. The specific model proposed by vdHBNR is a close binary in which a white dwarf accretes mass from a more massive main sequence (or slightly evolved) star. A detailed evolutionary scenario was developed, and a population synthesis study was carried out by Rappaport, DiStefano & Smith² (hereafter RDS). The result was that, even when a fairly strict set of criteria were used to identify supersoft sources, we computed that the Milky Way and M31 should each house on the order of a thousand active supersoft sources. Although there are uncertainties inherent in any such calculation, the bottom line was that the steady-nuclear-burning white dwarf accretor model passed one crucial test. That is, it seems to represent a phase in the evolution of a large enough fraction of primordial binaries, that a significant number of such systems should be actively involved in mass transfer today.

Perspective

The steady-nuclear-burning region, indicated in the figure below, can be physically realized in one of at least two ways. The first is in the close binaries considered by vdHBNR and by RDS; 4–5 of the ~ 15 well-studied supersoft sources have properties that seem compatible with this model. The second physical realization is in longer-period white-dwarf-containing binaries in which the donor star is a fairly well-developed giant; 3–4 of the well-studied supersoft sources are apparently symbiotics of this variety. Systems that fall just below the steady-nuclear burning

region will experience occasional nova outbursts. Novae which are still experiencing or which have recently experienced an episode of nuclear burning may also be expected to exhibit the properties of luminous supersoft sources, and indeed at least one of the well-studied sources was a recent nova. See Hasinger³ and Kahabka⁴ for reviews of the observations. It is also to be expected that systems for which $\dot{m}$ is just above the region associated with steady nuclear burning should pass through phases in which they exhibit supersoft behavior. Apart from the white dwarf models described above, it may be possible for accreting neutron stars or black holes to exhibit supersoft behavior.

The first-principles population synthesis study of RDS leads to a population on the order of ~ 1000 for the steady-nuclear-burning white dwarf accretors in close binaries alone. Thus, the total population of presently active sources may be larger.

OBSERVATION-BASED DERIVATION OF THE POPULATION

From the beginning it was recognized that, because radiation in the wavebands emitted by supersoft sources is strongly absorbed by the interstellar medium, the number of observed sources was likely to be only a fraction of the number of active emitters. A quantitative analysis to estimate the size of the active population, based on the sources already detected by ROSAT, was done by DiStefano & Rappaport⁵ for each galactic system in which supersoft sources have been observed. The approach we took is to “seed” each system with a set of supersoft sources. The ISM of each galaxy was also modeled, so that, for each individual source, we could compute the column density of neutral hydrogen between it and the Earth. By interfacing with the PIMMS software (Mukai⁶), we were able to compute the ROSAT PSPC count rate generated by each source and to thereby determine whether, given ROSAT’s coverage of the relevant part of the sky, the source would have been detected. A Monte Carlo analysis led to the following ranges of values: for M31, 500 – 3000 sources; for the Magellanic Clouds, 20 – 100 sources; and for the Milky Way, 400 – 2000 sources. We also predict that M33 should house roughly 250 supersoft sources.

We note that our study was less sensitive to the lower temperature and lower luminosity sources, so that, should the total underlying population contain a larger fraction of such sources than we considered, our estimates would be underestimates. Furthermore, sources which might be (1) largely locally obscured by, for example, a thick accretion disk, or are (2) not presently luminous, were not covered by our analysis and would therefore supplement our estimate of the underlying population.

SUPERSOFT NEBULAE

On the one hand, the population estimates summarized above may be viewed as encouraging, since they indicate that supersoft sources may form a significant galactic population. On the other hand, these estimates may be viewed as discouraging, since they indicate that ROSAT and its near successors are not sensitive to the majority of the members of this population. We can “make the best of a bad situation”, by utilizing the circumstances that make X-ray detection so difficult—the softness of the emitted radiation, and its consequent proclivity for interaction with the surrounding interstellar medium (ISM). The theory of the nebulae which may be associated with luminous supersoft sources has been studied by Rappaport, Chiang, Kallman, & Malina⁷ (hereafter RCKM). Their observability depends on the properties of the source (luminosity and temperature) as well as the properties of the ISM. For source properties appropriate to supersoft sources, and for local ISM densities $\sim 3 \text{ cm}^{-3}$, typical nebular radii are $\sim 5 \text{ pc}$. During an optical survey of nine of the Magellanic Cloud supersoft sources (Remillard, Rappaport, & Macri⁸), one (CAL 83) was observed to have a nebula with properties compatible with the theoretical predictions of RCKM.

IMPLICATION OF SUPERSOFT NEBULAE

Should at least a subset of supersoft sources be associated with nebulae of the type described above, then possibly the most significant implication would be our ability to conduct systematic surveys for supersoft sources, and to study individual sources, even in distant galaxies. Those supersoft sources which illuminate the surrounding ISM may be discovered and identified through optical line emission of

the nebulae. The intensity in individual lines can be large, with, for example 2–5% of the bolometric luminosity ultimately emerging in the 5007 line of [O III]. Thus, narrow band imaging alternating with off-band imaging can be used to identify such nebulae. This observational approach has been used to study another class of astrophysical nebula, planetary nebula. In fact, it was noted by Di Stefano, Paerels, & Rappaport⁹ that the supersoft nebula luminosity function (SNLF) in the 5007 line of [O III] peaks near the cut of the planetary nebula luminosity function (PNLF). (See the figure above.) The PNLf, particularly near the cut-off has been well studied, since its apparently universal character allows it to be used to as measure of intergalactic distances.

TYPE Ia SUPERNOVAE

The subset of supersoft sources composed of accreting white dwarfs may include progenitors of type Ia supernovae. The rate at which such supersoft sources might undergo supernova explosions has been calculated for a variety of scenarios by RDS. For at least two of the scenarios, the supernova rate is comparable with the rate inferred from observations. A further piece of work (Di Stefano¹¹) utilizes the connection with supersoft nebulae, to compute potentially observable properties of possible type Ia progenitors.

IMPLICATIONS OF SUPERSOFT SOURCES

Relative to other X-ray binaries, supersoft sources are likely to exist in large numbers, with a galaxy like our own containing on the order of ~ 1000 sources, regardless of the fundamental nature of the sources. The radiation they emit is highly interactive with the ISM. Thus, in regions in which the local density of the ISM is high enough (on the order of a few atoms cm^{-3}), supersoft sources may be associated with distinctive nebulae. This opens the possibility that supersoft sources can be systematically studied, even in distant galaxies. Another interesting possible implication of the existence of supersoft sources is model-dependent—i.e., if some subset of them are accreting white dwarfs, then some may be progenitors of type Ia supernovae. In the oral presentation of this talk, an analogy between luminous supersoft X-ray sources and the tentacles of an octopus was drawn. The analogy seems apt, in that the implications associated with the existence of this class of object may reach into diverse areas of astrophysics.

REFERENCES

1. van den Heuvel, E.P.J., Bhattacharya, D., Nomoto, K., & Rappaport, S.A. 1992, *A&A*, **262**, 97-105.
2. Rappaport, S., Di Stefano, R., & Smith, J.D. 1994, *ApJ*, **426**, 692.
3. Hasinger, G. 1994, in ‘*The Evolution of X-ray Binaries*’, Ed. S. S. Holt & C. Day (New York: AIP)
4. Kahabka, P. 1995 this volume.
5. Di Stefano, R., & Rappaport, S. 1994, *ApJ*, **437**, 733.
6. Mukai, K. 1993, *Legacy*, **3**, 21.
7. Rappaport, S., Chiang, E., Kallman, T., & Malina, R. 1994b, in press .
8. Remillard, R., Rappaport, S., & Macri, L. 1994, *ApJ*, in press.
9. Di Stefano, R., Paerels, F. & Rappaport, S. 1994, submitted to *ApJ*.
10. Di Stefano, R. 1995, submitted to *ApJL*.