11. MODELS FOR COMPACT X-RAY SOURCES

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Abstract. A statistical analysis of the UHURU catalogue of X-ray sources leads to the following conclusions. If the weak sources are omitted, there is a strong concentration to low galactic latitude but the absence of a strong background and the presence of some strong sources at low galactic longitude indicate an appreciable number of sources of luminosity $L \sim 10^4 L_\odot$ in the vicinity of the 'nuclear bulge'. This region generally suggests 'stellar population II' and therefore stars of small mass. However, there is some suggestion of a second class of sources, distributed in the galactic plane like 'stellar population I' and suggesting large stellar masses.

There are three possible types of simple X-ray spectra, (a) optically thin bremsstrahlung, (b) black-body spectrum, and (c) power-law spectra. In this talk only theoretical models for type (a) are reviewed, including accretion, rotation and vibration for a white dwarf star and cocoons around a neutron star.

1. Introduction

This is merely the first of three review talks on theoretical models for compact X-ray sources. I will start (Section 2) with a topic which is not strictly theoretical but provides an important input for such models: Over 100 individual X-ray sources (mainly from the UHURU catalogue of sources) are now known and some information about luminosities, lifetimes and stellar populations can already be obtained from statistical data.

A multitude of theoretical models will be discussed and there are even different ways to classify them. Let us start with one type of classification that refers to the observational data rather than models for them, namely the type of X-ray spectral distribution. There are at least three simple kinds of spectra which, in principle, should be readily distinguishable: (a) Optically thin (Bremsstrahlung or 'free-free') thermal emission. The most characteristic feature of such a distribution is that it is 'flat-topped', but at high frequencies it falls off exponentially and the 'Boltzmann factor' determines a temperature T_x. (b) Black-body radiation, characterized by temperature T_x. (c) An inverse power-law spectrum with some index n, characteristic of synchrotron radiation.

The type of X-ray spectrum refers not so much to the primary energy source, but to conditions in the gaseous region where this energy is converted into X-ray emission, and depends on the size of this region. The most exciting speculations concern the recently discovered periodic X-ray sources and the easiest kinds of theoretical models to build for such sources involve small emitting regions, not much larger than the size of a neutron star. Such models will be discussed in the later reviews and usually will predict complicated spectra, but somewhat resembling types (2) and (3) above. Unfortunately, rather little is known directly about the spectra of the most interesting sources. However, for at least one source, Sco-X1, the spectrum is known to be of type (1) – optically thin Bremsstrahlung from regions of size comparable with (or slightly larger than) radii of white dwarf stars. I will

Bradt and Giacconi (eds.), X- and Gamma-Ray Astronomy, 135–142.

discuss (Section 3) models only for sources of this relatively large size (10^4 to 10^5 km), even though it may turn out that none of the periodic sources are of this size.

2. Statistical Data

At the moment we have no accurate distance-indicators for *individual* X-ray sources, but we shall nevertheless be able to draw some statistical conclusions about the overall spatial distribution of galactic sources. Such conclusions, although preliminary, are useful in at least two ways: (1) If one can establish a rough distance-scale one also has a rough luminosity function and some information on general energy requirements. (2) If one can identify the spatial distribution of galactic X-ray sources with that of one of the stellar populations, one has some indirect indications about the masses of such sources: It seems reasonable to assume that X-ray emission occurs during a relatively short-lived phase in the evolution of a single or binary star. Stars of population II in an active evolutionary phase have relatively small masses, $M \sim M_{\odot}$. If some class of X-ray sources is distributed with population II it is then likely that the star (or at least one of the two stars in the case of a binary) required to initiate the X-ray phenomenon need not be very massive.

The UHURU catalogue (Giacconi *et al.*, 1972) of X-ray sources lists intensity I (in the 2–6 keV energy range in counts $\mathrm{s}^{-1}/840\ \mathrm{cm}^2$ i.e. units of approximately $1.7 \times 10^{-11}\ \mathrm{erg\ s}^{-1}/\mathrm{cm}^2$) and angular position for about 125 sources. This list contains some extragalactic sources, but contamination due to them is unimportant for intense, low-galactic latitude sources: We restrict ourselves to sources with $I > 5$ and eliminate a few positively identified extragalactic sources (in the Virgo, Coma and Perseus clusters, in NGC 5128 and 5 sources in the Magellanic Clouds). About 75 sources remain and their distribution in galactic latitude b and longitude l is indicated in Table I. Half the total solid angle away from the galactic plane ($|b| > 30°$) has only about 3 sources and extragalactic sources are indeed unimportant in this list.

TABLE I

The stronger sources in the UHURU catalogue, with numbers in bins of galactic latitude b and longitude l[a]

b(°) / l(or 360° − l)	0 to 1.25	1.25 to 2.5	2.5 to 5	5 to 10	10 to 20	20 to 30	> 30	
0–45°	11	7	6	10	4	2	0	40
45–90°	6	3	1	2	2	2	2	18
90–180°	4	2	5	1	3	1	1	17
								75

[a] Note that these numbers do not take into account the variable exposures to the various celestial regions. However, the uniformity of the survey was sufficient to permit the conclusions drawn in this paper.

https://doi.org/10.1017/S0074180900100336 Published online by Cambridge University Press

The sources are highly concentrated to low galactic latitudes (median $|b| \sim 4°$) and one might at first expect the sources to be distributed like extreme population I stars. This extreme assumption would have the following consequences which we shall see are unlikely: The median galactic height of extreme population I (see Figure 1) is $|z| \sim 80$ pc; if we average the data in Table I over galactic longitude l,

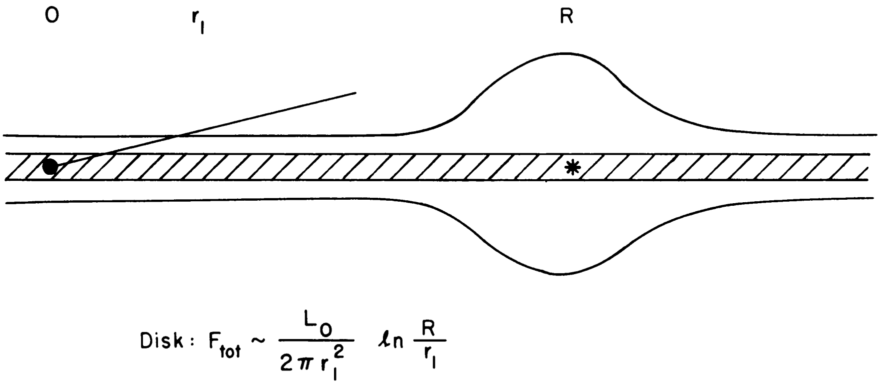

Fig. 1. A schematic view of the galactic plane (shaded region) occupied by stellar population and the outline of the 'intermediate population II' distribution including the 'nuclear bulge'.

the latitude distribution then gives us information on distances to the brighter sources. Assuming the same absolute luminosity L_X for all sources, the latitude distribution of the 18 brightest sources coupled with the assumption of $|z| \sim 80$ pc would then require a source density of about one source per cylinder of radius 250 pc and the intensity distribution (of the ~ 18 sources with $I > 200$) would require a mean X-ray luminosity of $L_X \sim 100\, L_\odot$ ($\sim 4 \times 10^{35}$ erg s^{-1}). For resolved sources located in the thin galactic plane, the number $N(I)$ with intensity exceeding I should be of form

$$N(I) = b/I \tag{1}$$

with $b \approx 4{,}000$. A source with $I \sim 200$ is at a distance of $r_1 \sim 1.1$ kpc and the weakest source admitted in our Table I with $I \sim 5$ is at ~ 7 kpc (compared with a distance of ~ 10 kpc to the center of our Galaxy). We have heard from Tananbaum that (for $I \lesssim 200$ where the statistics is good enough so we need not worry about fluctuations) $N(I)$ does not follow Equation (1) at all but approximates $N(I) \propto I^{-0.4}$. The failure to resolve a large number of sources with $I < 200$ would then represent a discrepancy; further, the unresolved weaker sources would contribute to a strong background (highly concentrated to very low latitudes $|b|$): With the radial distance to the galactic center assumed to be $R_G \sim 10$ kpc, this background would have to be $B \sim 3000$ counts per radian (s 840 cm^2), roughly given by

$$B \sim 2b \ln(R_G/r_1). \tag{2}$$

https://doi.org/10.1017/S0074180900100336 Published online by Cambridge University Press

The observed background in the galactic plane reported by Cooke *et al.* (1969) and Gursky (1972) is much smaller than that and Clark mentioned an even smaller value at this Symposium.

Arguments of this kind (Ryter, 1970; Setti and Woltjer, 1970) were already suggestive before the UHURU data and now seem quite convincing. Although we have assumed above a single absolute luminosity, our arguments would not be weakened appreciably if we allowed a more general luminosity function as long as we assumed a median height of $|z| \sim 80$ pc and have to fit the observed latitude dependence. If one assumed a larger median height $|z|$ (but still assumed a disk without any 'bulge'), the calculated distance r_1 would increase in proportion to $|z|$ but (since our value of R_G/r_1 was almost 10) $|z|$ would have to be increased a lot to weaken the discrepancy appreciably.

In reality, the sources in Table I are not distributed uniformly in galactic longitude l, but have a concentration within 30° or 45° of the galactic center (especially for the stronger sources). The angular distribution of this concentration is similar to that of the 'nuclear bulge' (the innermost few kpc in diameter and a few hundred pc in height, see Figure 1) which contains about 80% of the total mass of our Galaxy (Inanen, 1966). Much of the total X-ray output of the whole Galaxy is thus likely to come from about 20 to 50 intrinsically bright sources with a mean luminosity of $L_X \sim 2 \times 10^4\, L_\odot \sim 10^{38}$ erg s^{-1}, with a spatial distribution through the Galaxy similar to the overall distribution of ordinary stars. The five sources in the Magellanic Clouds (total mass $\sim 10\%$ of our Galaxy) corroborate this picture (Leong *et al.*, 1971).

The indirect arguments above then suggest that these bright X-ray sources in the 'nuclear bulge' do not require particularly massive stars as progenitors. This argument cannot be made rigorous at the moment because a concentration of massive stars in the 'nuclear bulge' of our *own* galaxy cannot be ruled out with certainty. However, data from other galaxies (and the distribution of neutral hydrogen gas in our own) make such a concentration unlikely.

Although there is probably no physical connection, the bright X-ray sources have a similar luminosity and spatial distribution to planetary nebulae but are less numerous by a factor of about 100. X-ray sources with known, rapid intensity-variations represent an interesting but numerically small subclass of sources. Although one cannot be quantitative at the moment because of the small numbers involved, the angular distribution of the fluctuating sources is strikingly different: No concentration near the 'nuclear bulge' is apparent and the data is consistent with an 'extreme population I' distribution (e.g. with a concentration in spiral arms). It is then quite likely that the rapidly fluctuating sources are associated with massive, young stars.

The distribution of received intensity I for all the galactic X-ray sources seems to suggest a break in the distribution. Interstellar absorption of soft X-rays (Seward *et al.*, 1972) gives distance estimates for some of the galactic sources and hence gives absolute luminosities: This data gives firmer evidence for a second group of weaker sources with $L_X \sim (10^{35}$ to $10^{37})$ erg s^{-1} in addition to the strong sources with $L_X \sim 10^{38}$ erg s^{-1} already mentioned. Unfortunately we do not have enough data yet to tell whether the second group is an entirely distinct one with a separate spatial distribution (as is probably the case for the fluctuating sources) or merely the low-luminosity tail of one wide distribution. Incidentally, if there is a separate class of source with 'extreme population I' distribution then it should contribute appreciably to the source counts at the faint end. If the integrated intrinsic luminosity function of the strong sources in the 'nuclear bulge' is of form $N(L_X) \propto L_X^{-\alpha}$, then a comparison with the observed overall $N(I) \propto I^{-0.4}$ shows that α must be less than 0.4.

Some theoretical comments and questions seem in order: The group of bright sources associated with the nuclear bulge probably have a star of mass $M \sim M_\odot$ at the center of each source and their luminosities L_X cluster close to but probably do not exceed $\sim 10^5 L_\odot$. For a given stellar mass M and opacity coefficient κ, there is a critical luminosity

$$L_{\text{crit}} \sim 4\pi cGM/\kappa \tag{3}$$

such that radiation pressure would overcome gravity if L_X exceeded L_{crit}. With Thomson scattering opacity and $M \sim M_\odot$, L_{crit} is close to the observed upper range of $\sim 10^5 L_\odot$ and this coincidence might be of physical significance. Much of the theoretical discussion will be about compact X-ray sources with $R \lesssim 10^5$ km. This is certainly the case for the rapidly fluctuating sources, but for only a fraction of the brightest sources (near the nuclear bulge) have rapid fluctuations been confirmed so far. Are the remaining bright sources in fact also compact or are these a completely different class, possibly associated with supernovae remnants? For the genuinely compact sources, on the other hand, we do not know their mass distribution nor whether they represent a homogeneous class.

3. Models for Optically Thin Emitters

A large number of rival models for various kinds of galactic, compact X-ray sources have already been proposed and more are likely to follow. When more observational data is available on the X-ray (and optical) spectra, on time variations of intensity and spectrum and on interaction with any companion, hopefully the choice will narrow. At the moment the number of models is large because each model is complex and at least a three-dimensional classification-scheme is needed even to characterize a model qualitatively:

(1) A compact, stable type of star at the center of the emitting region is usually invoked, to provide a gravitational field to contain the emitting gas and/or to provide an energy source. Since the emitting regions have sizes $\leqslant 10^6$ km, ordinary stars are ruled out, but white dwarfs, neutron stars, black holes (and some further variants) are all possibilities. (2) Some form of primary energy source is required, which could be gravitational energy released by accretion, rotational kinetic energy of the central star, or nuclear energy production or vibrational energy (acting as an intermediary). (3) The primary energy source somehow has to energize the material which eventually emits the X-rays. Here there is even more variety in the 'transmitting agent' (relativistic

https://doi.org/10.1017/S0074180900100336 Published online by Cambridge University Press

particles, low-frequency electromagnetic radiation, compression, direct heating, etc.) and in the type, location and size of the final X-ray emitter (small, optically thick stellar atmosphere or large, dilute optically thin gas cloud or a relativistic plasma emitting non-thermally, etc.).

The emitted X-ray spectrum depends most directly on the choice in (3), but indirectly also on (1) and (2). For a few sources, most notably for Sco-X1, we have fairly good observational evidence for an optically thin thermal Bremsstrahlung spectrum with temperature of order $T_X \sim 10^8$ K from a region typically of size $R \sim (10^4$ to $10^5)$ km. I will briefly review only models relevant for emitting regions of this size. We do not know whether any of the sources with intricate periodic intensity variations (and suggestions of a binary system) are of this type. If one only has to fit luminosity L_X, temperature T_X and size R (and irregular intensity fluctuations over seconds or longer), one finds that most of the models have sufficient parameters to enable a fit. The overall energy requirements for the whole Galaxy are also not too severe: The number of observed sources could be accounted for if, for instance, an appreciable fraction of stars at some stage of their evolution emitted $L_X \sim 10^4\ L_\odot$ for a few hundred years; the required amount of energy could be supplied by burning $\sim 10^{-4}\ M_\odot$ of hydrogen or gravitationally by adding a mass of $\sim 10^{-2}$ $M_\odot$ to a white dwarf. I cannot give a *critical* review – each of n^3 differerent models works just fine in the absence of more observational data – but will at least list those models that have already been discussed.

We are considering emitting regions of size comparable with (or slightly larger than) that of typical white dwarfs ($\sim 10^4$ km). The simplest kind of models are then likely to be those which invoke a white dwarf as the central star. Of the various primary energy sources, gravitational energy released by accretion is probably the easiest to visualize (but not the easiest to calculate with, nor the most economical of mass). Accretion has been most popular with champions of neutron stars (Shklovsky, 1967; Shwarzman, 1970; Sofia, 1970), in which case the main emitting region would be much smaller. However, mass-loss from a larger companion-star in a close binary system which gets accreted onto a white dwarf star does give emitting regions of the size we are considering (Cameron and Mook, 1967; Prendergast and Burbidge, 1968). If the accreted atoms moved under free fall conditions and then gave up their energy in just a few collisions, color-temperature of the emitted radiation would be of order $T_X \sim 10^9$ K rather than $\sim 10^8$ K. In reality, the infalling material has to give up angular momentum and flows through a rotating disk of gas, giving up its energy more slowly so that a smaller value of T_X seems reasonable. Rates for angular momentum transfer and accretion rates for a given binary system cannot be calculated in an honest, a priori manner at the moment, but the rate required to give the observed luminosity L_X is of course known. As mentioned, L_X is close to L_{crit} so that radiation pressure may even act as a servomechanism to control the accretion rate to keep L_X/L_{crit} small but not too small.

If sufficient material ($>10^{-4}\ M_\odot$) still rich in hydrogen should be accreted onto the surface of a white dwarf, the hydrogen may ignite and the *H–He* conversion could release appreciably more energy than was released in gravitation. The vibration period of a dense white dwarf can be as short as a few seconds (Gribbin, 1971). A model has been suggested (Blumenthal *et al.*, 1972) where kinetic energy of large amplitude vibrations drives shockwaves out from the atmosphere of a white dwarf and heats outer layers to X-ray temperatures. More detailed calculations (Katz, 1972) show that sufficient X-ray emission is obtained from shock-heating only if the vibrations are violent enough to disrupt much of the atmosphere. Nevertheless, hydrogen-burning in intermittent flashes might power violent vibrations and accretion might replenish lost material. Magnetically controlled flares (somewhat analogous to solar flares) could also give non-thermal (inverse power-law) X-ray emission from a white dwarf atmosphere (Blumenthal and Tucker, 1972).

Rapidly rotating white dwarfs with a strong magnetic field emit 'pulsar radiation' which could (via the intermediary of relativistic particles) heat material to X-ray temperatures near the 'speed-of-light circle'. For ordinary, dense white dwarfs the emitting region is then rather large, $R \sim 10^6$ km (Apparao, 1971). However, rapidly rotating condensed stars of mass somewhat greater than the Chandrasekhar limit are also theoretically possible and would have a rotation period of only a few seconds (Ostriker and Bodenheimer, 1968). Pulsar radiation from such an object (Van Horn and Lamb, 1972) could give somewhat smaller emitting regions; on this model periodic intensity variations would reflect the rotation period which *shortens* as the star loses energy (in contrast with ordinary pulsars).

A number of models invoke 'pulsar radiation' derived from the rotational kinetic energy of a neutron star (as in 'ordinary pulsars') as an intermediary to power some emission mechanism. In most models the emitting region is either well inside the 'speed-of-light circle' (Coppi and Treves, 1971) or near it (Apparao, 1972), so that the emission radius R is typically less than 10^4 km. In one model (Davidson *et al.*, 1971) the emission region is a gaseous coccoon held out at distances R much larger than the speed-of-light radius by the Poynting-Robertson effect, so that R is large even for a rapidly rotating neutron star. In this model (and probably also for a rapidly rotating white dwarf) one has a gaseous 'doughnut' in the equatorial plane which favors the ejection of particles or of electromagnetic radiation (as proposed recently by Rees) along the two polar directions to form a double radio source (as reported for Sco X-I). Finally, one model (Jackson, 1972) uses relativistic electrons accelerated by a rotating neutron star to make nonthermal X-rays by the inverse Compton-effect on optical photons coming from a companion B-star.

Although it seems hard to select out 'the best' model at the moment, hopefully the situation will change with further observational data. Spectral details and their theoretical analysis (Felten and Rees, 1972) will help, both for the continuous and the line spectrum. For instance, the present upper limit on the iron-line intensity for Sco X-I already rules out models with large emitting regions ($>10^5$ km), the positive identification of this line would rule out very small ($<10^4$ km) emitters. More information on time-variations of intensity and spectrum, especially when there are periodic variations, will also help.

Acknowledgements

I am grateful to J. Katz, J. Ostriker, F. Pacini and M. Rees for interesting discussions. This work was supported in part by National Science Foundation Grant GP-26068.

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