SPECTROSCOPIC AND STATISTICAL PROPERTIES OF X-RAY SOURCES*

(Invited Discourse)

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1. Introduction

Among the little less than 50 known X-ray sources, only 7 had been identified with optical objects at the end of 1968 (Gratton, 1968) and a couple or so have been added during the present Symposium; some identifications are still uncertain.

It is remarkable that, apart from the case of Supernova remnants, one of which was the first X-ray source to be identified, all other objects which have been predicted as likely sources of X-rays have never been observed as such. This is by no means intended to discourage theoretical predictions like those contained, for instance, in a recent paper by Biermann (1969). Since X-rays from the sun have been observed, it is obvious to assume that many more stars will emit more or less intense X-ray fluxes, and it is quite reasonable to look first at those which are considered more likely. But it is clear that all predictions must be regarded as very uncertain until we do not understand better the nature of the most powerful sources. Hence the discussion must be necessarily limited to those sources for which direct observational evidence is available.

The present evidence shows quite clearly that these sources belong to (at least) three different categories.

(a) Galactic extended objects.
(b) Galactic star-like objects.
(c) Extragalactic objects.

Only one object of class (c) is at present known with a reasonable certainty (the radiogalaxy M87) and this class will not be discussed here.

Objects of class (a) usually have an X-ray spectrum with a strong tail towards the high energies; two of them have been known since some time and one more has been added during this Symposium by the ASE group (Gorenstein *et al.*, 1969); the position

* According to the original program a discussion of the spectral properties of the X-ray sources in the optical region was to be presented at the Symposium by E. M. Burbidge; the Organizing Committee invited also A. Sandage to discuss optical identifications, relationships with known optical objects and other astrophysical problems. Unfortunately Sandage was unable to attend the Symposium and a few weeks ago E. M. Burbidge wrote that she also could not come.

Therefore the present paper was prepared rather hurriedly to cover these points, mainly with the purpose of introducing the discussion on them. The author asks to be excused for its many deficiencies and hopes that the optical astronomers present at the meeting will make some compensation and perhaps supply more new material and subject for discussion.

L. Gratton (ed.), Non-Solar X- and Gamma-Ray Astronomy, 162–172.

of the latter coincides convincingly with Tycho's supernova of 1572. There is therefore little doubt that objects of this class are remnants of supernova explosions. It is quite possible that all supernova remnants would show X-ray emission if observed with detectors of sufficient sensitivity, although of course this cannot be proved.

Objects of class (b) have a much steeper X-ray spectrum than those of class (a). In the high energy region Sco X-1 – the prototype of class (b) objects – is fainter than the Crab nebula, although the reverse is true in the 1–10 keV domain. The four objects for which an identification exists, Sco X-1, Cyg X-2, GX 3+1, Cen XR-2 (the last two objects are still doubtful), have optical counterparts of star-like appearance showing peculiar light variations and spectral features strongly resembling those of ordinary Novae at minimum light.

In the rest of this paper I will shortly summarize the published results on the spectra of the four objects assigned to class (b); a short discussion will follow concerning the evidence which can be obtained from the distribution of known X-ray sources on the celestial sphere.

2. Optical Spectra of the Star-like X-Ray Sources (Class b)

1. Scorpio X-1

The identification of this source (Sandage *et al.*, 1966) on the basis of the accurate position obtained by the ASE and MIT groups (Gursky *et al.*, 1966) is beyond doubt. Observations of the spectrum have been published by Sandage *et al.* (1966), Ichimura *et al.* (1966), Jugaku (Babcock, 1967), Wallerstein (1967), Westphal *et al.* (1968).

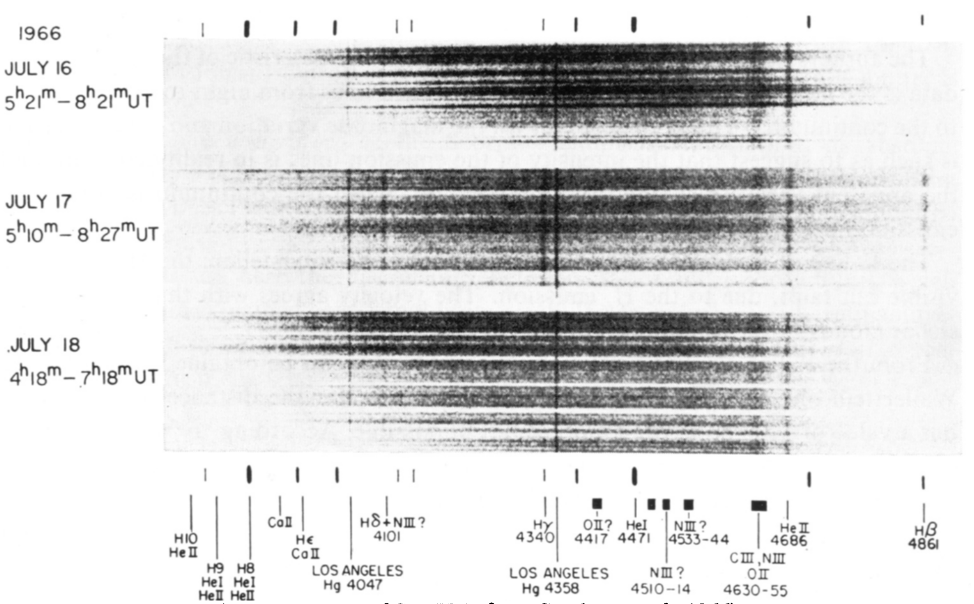

Fig. 1. Spectra of Sco X-1 (from Sandage *et al.*, 1966).

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Figure 1 is from Sandage *et al.* paper of 1966 and Figure 2 from that by Westphal *et al.* (1968); on the latter various identified emission lines are marked. They correspond to the Balmer series up to H_{12}, to He I, He II (the line 4686 is the strongest in the whole spectrum), O II, N III. The identification of the lines marked Fe II is considered as uncertain by the authors. No forbidden lines were convincingly identified.

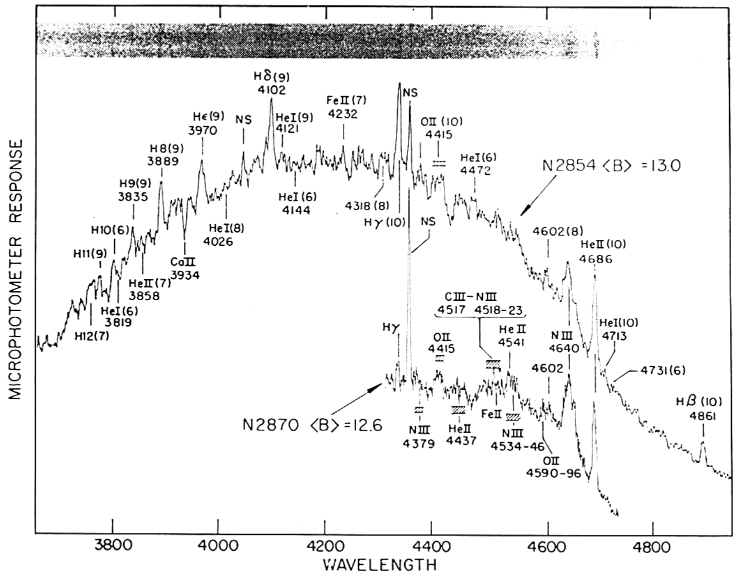

Fig. 2. Microphotometer tracings of spectra of Sco X-1 (from Westphal *et al.*, 1968).

The authors note that "the most impressive single characteristic of the spectroscopic data is the large intensity variation of the hydrogen lines from night to night, relative to the continuum". This is correlated with the magnitude variation and the correlation is such as to suggest that the intensity of the emission lines is in reality constant and the apparent variation is due to the continuum; when the continuum is fainter the emission lines appear brighter by contrast.

The K line of Ca II in absorption is almost certainly interstellar; the H line is also visible but faint, due to the H_ε emission. The velocity agrees with that of the interstellar clouds in the same region of the sky (Wallerstein, 1967).

From the K line a reliable estimate of the distance can be obtained; according to Wallerstein one obtains thus a lower limit of 270 pc for the distance of the source, but a value of 1000 pc or even more is not impossible. According to Westphal *et al.* (1968) from Wallerstein's ratio for the Ca doublet, K/H = 1.4, a distance of 240 pc is obtained, in fair agreement with Wallerstein's lower limit.

In view of the many uncertainties Westphal *et al.* favour a distance of 500 pc; with a B-absorption of 0.9 mag the absolute magnitude of Sco X-1 is

$$M_B = 3.6;$$

at this distance the total energy output in the X-ray spectrum is

$$P = 2 \times 10^{37} \text{ erg sec}^{-1},$$

or 10^3 or 10^4 times the power radiated in the optical spectrum.

This distance estimate agrees well enough with that from observations of the soft X-ray flux, which however gives contradictory results. I think that most astronomers would feel inclined to trust the interstellar line results and to agree that a distance $300 < D < 1000$ pc is quite realistic. Of course the ratio between the X-ray and optical fluxes is almost independent of distance.

Radial velocity measurements give very interesting and puzzling results. From the three strongest lines (He II 4686, H_γ and H_δ) it is found that on two nights the He II and H lines were changing the respective velocities in an opposite way: on July 17, 1967, He II changed from −155 to −215 km/sec, H_γ from −125 to −35 km/sec, H_δ from −192 to −112 km/sec. A similar variation occurred in the following night.

Thus not only the velocities from He II and from H were different but the former increased, while the latter decreased in absolute value. Also the H_δ velocities were systematically more negative than those of H_γ.

According to Westphal *et al.* (1968) simple binary motion cannot explain these variations; gas streams in which atoms of different excitation move in a widely different way are of course not impossible to imagine, but clearly more observations are needed.

It has been suggested by Braes and Hovenier (1966), Blaauw (1967), O'Dell (1967) that Sco X-1 might be a member of the Scorpio-Centaurus association. The best evidence should be based from the proper motion, which according to Gatewood and Sofia (1968) is in very good agreement with that corresponding to the Scorpio stream. But there is some disagreement between proper motions from different sources (Luyten, 1966; Johnson and Stephenson, 1966; Klare 1967) and the matter is still doubtful.

If Sco X-1 were a member of the Scorpio-Centaurus Association, its absolute magnitude – $M_V = +7$ – would be difficult to reconcile with the distance obtained from the interstellar lines (Wallerstein, 1967). This point is very important and should be further discussed.

I will not discuss here the discrepancy between X-ray and optical fluxes which results if both are explained as thermal bremsstrahlung from an optically thin source, nor the correlation between X-ray, optical and radio variations (Chodil *et al.*, 1968, Ables, 1969).

2. *Cyg XR-2*

The identification of Cyg XR-2 (Giacconi *et al.*, 1967) may be also considered fairly well established. Spectroscopically this is an even more complicated object than Sco X-1; published results are due to Lynds (1967), Burbidge *et al.* (1967), Kristian *et al.* (1967), Kraft and Demoulin (1967); see Figure 3.

The general impression is that of an object more or less similar to Sco X-1, on whose

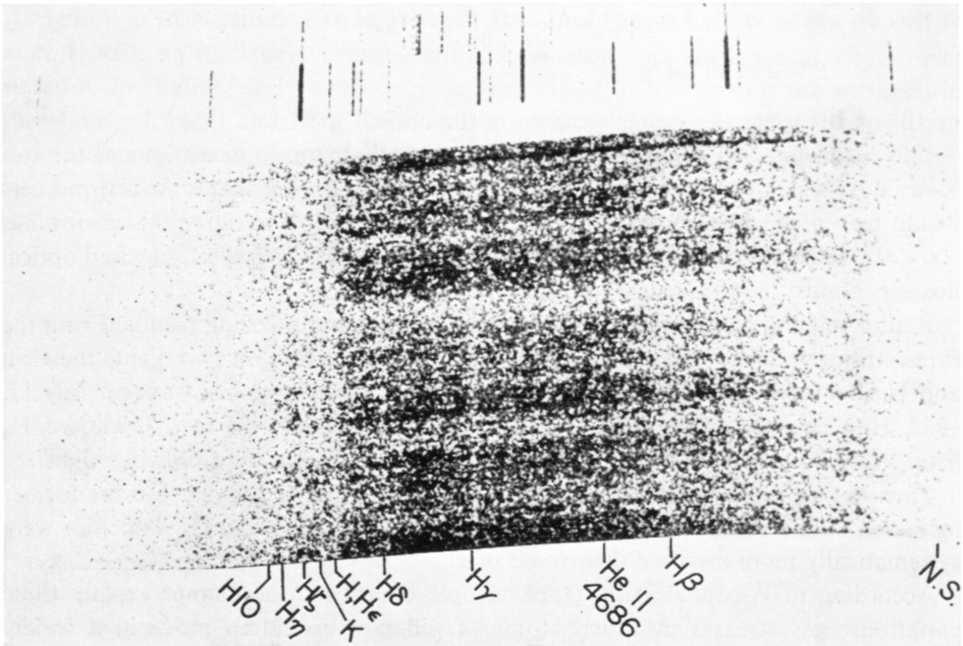

Fig. 3. Spectrum of Cyg X-2 (from Lynds, 1967).

spectrum another spectrum closely resembling that of a G subdwarf is superimposed. This somewhat simplistic interpretation is supported by the photoelectric scanner photometry by Peimbert *et al.* (1968); they conclude that the observed continuum may be explained as due to at least two sources: one flat or of an early type (O9 V) component and one of a late type (later than F2 V). The flat spectrum is in fair agreement with the prediction from the observed X-ray flux, if one assumes that it is due to thermal bremsstrahlung. However the attenuation of the bremsstrahlung radiation is more than what might be expected from interstellar absorption alone.

The G-dwarf shows a large and variable negative velocity. By assuming that it is due to a 'normal' G or late F subdwarf (absolute magnitude $M = +5$) a distance of 700 pc may be obtained for the source; this reduces to little more than 500 if interstellar absorption is considered.

The absolute value of the X-ray flux of Cyg X-2 is difficult to evaluate, mainly because the interstellar attenuation is not well known; apparently it is somewhat fainter than that of Sco X-1; a realistic estimate is about 10^{36} erg $\sec^{-1}$. Compared with the optical luminosity of a G-subdwarf (10^{33} erg $\sec^{-1}$) we get a ratio of 10^3 between the power radiated in the X-ray and in the optical domains. Like in the case of Sco X-1 this ratio is almost independent of the assumed distance.

The large variations of the radial velocity are not readily explained by orbital motion (Burbidge *et al.*, 1967; Kraft and Demoulin, 1967). If taken literally the average of the radial velocity would give a systemic velocity around -250 km/sec

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(Kristian *et al.*, 1967). But this interpretation is doubted by Sofia and Wilson (1968) mainly on the basis that the total mass would come out too large for a G-subdwarf; they suggest that a systemic velocity of about $\dot{-}120$ km/sec would be more consistent with a reasonable value of the mass. The difference between the observed velocity and this value should then be due to motion inside the system, which is also not easy to understand.

3. Cen XR-2 and GX 3+1

The identifications of the last two sources is still open to doubt. Cen XR-2 was identified by Eggen *et al.* (1968) with a previously known peculiar variable, WX Cen, mainly on account of the character of the light variation and of the spectroscopic behaviour which follow closely the pattern corresponding to the optical counterpart of Sco X-1. Figure 4 shows the spectrum published by these authors, who comment upon its close resemblance to that of Sco X-1.

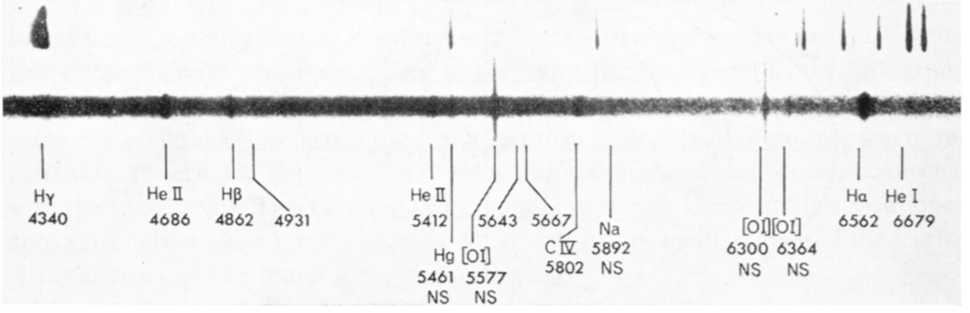

Fig. 4. Spectrum of WX Cen = Cen XR-2 (from Eggen *et al.*, 1968).

The emission lines are somewhat broader than those of Sco X1; the H_α line has a faint narrow extension at both sides of the stellar spectrum, which however may be probably due to the general diffuse H_α emission in this galactic region. A distance of 500 pc is obtained if the absolute magnitude of the object is the same as that of Sco X-1. As it is known the X-ray flux underwent a very large decrease of intensity during 1967.

The identification of GX 3+1 with a faint star with a peculiar spectrum was suggested by Blanco *et al.* (1968a) and later Blanco *et al.* (1968b) reported a spectrum with broad emissions of He II 4686 and O VI 3811 and 3843. Freeman *et al.* (1968) find however that the spectrum is not very similar to that of old Novae or Sco X-1, but is rather suggesting a Wolf-Rayet star or a 'supernova'. The star is situated inside a faint ring nebula.

3. Distribution of X-Ray Sources in Galactic Coordinates

It has been observed that the distribution of X-ray sources on the celestial sphere

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suggests some relationship with known objects and this might afford some clue to their nature.

The following classes of objects may conceivably be considered as reasonable candidates and have in fact been suggested:

(a) supernova remnants;
(b) old novae;
(c) Wolf-Rayet and related high temperature objects;
(d) pulsars.

Of course these objects do not exhaust the list, but I thought it better to confine myself to them; also all pulsars are at least potentially related to supernova remnants and viceversa.

The distribution in galactic coordinates of the 45 X-ray sources known at the end of 1968 is shown in Figure 5; like in other similar plots the concentration of these

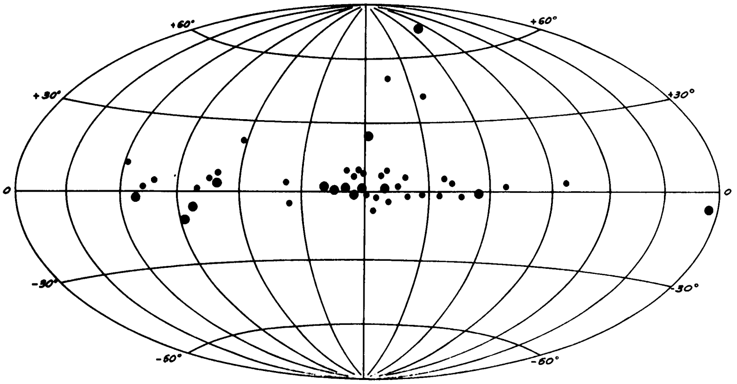

Fig. 5. Distribution of X-ray sources in galactic coordinates.

sources towards the galactic plane and towards the galactic centre is very striking and may be taken as an established fact.

Nevertheless it may be observed that since the experimenters are – reasonably enough – anxious to obtain at least some positive results during a flight, by far the majority of the experiments were planned in order to cover the galactic belt or a part of it as soon as the galactic concentration of the sources was discovered. Therefore the chances of discovery of a faint source at high galactic latitude is much smaller than at low latitude, especially if one takes into account the variability of many sources. In Figure 6 I tried to give some idea of how densely the different parts of the sky have been covered by the experiments whose results have been published before 1969. The corresponding selection effect should be considered in an accurate study of the distribution of the sources.

The relationship between X-ray sources and supernova remnants has been thoroughly discussed by Poveda and Woltjer (1968) and is of course proved by some known individual cases. But among the 10 possible identifications suggested in Poveda and Woltjer's paper, it was found that Vel XR-1 does not coincide with Vel X nor

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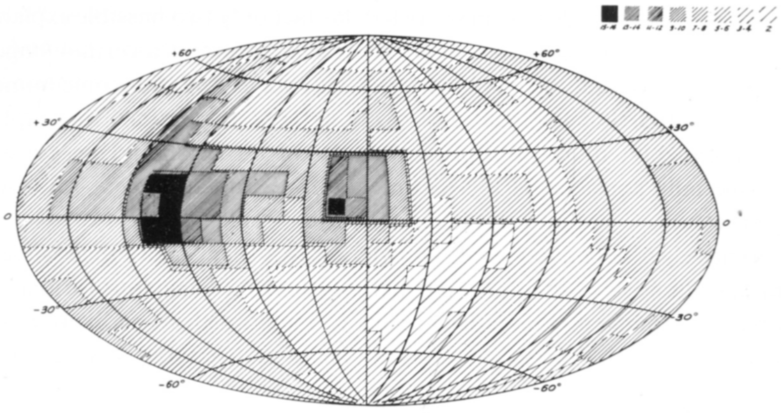

Fig. 6. Covering of the sky by X-ray experiments prior to January 1969. The shading of the various areas corresponds to the number of flights which covered the areas themselves.

with Vel Y (Gursky *et al.*, 1968) and Tycho's supernova is not coincident with the source Cep XR-1 observed by Friedman and his coworkers (Friedman *et al.*, 1967) but with another source which was missed by them and discovered later by the ASE group (In this volume).

On the other side the distribution of supernova remnants does not show any remarkable clustering in the direction of the galactic centre and seems more connected with the spiral arms. This fact and the examples of wrong identifications mentioned above strongly suggest – in my opinion – that only a very small number of the known X-ray sources will be found to belong to this class.

The distribution of old Novae is shown in Figure 7 as given by Payne-Gaposchkin

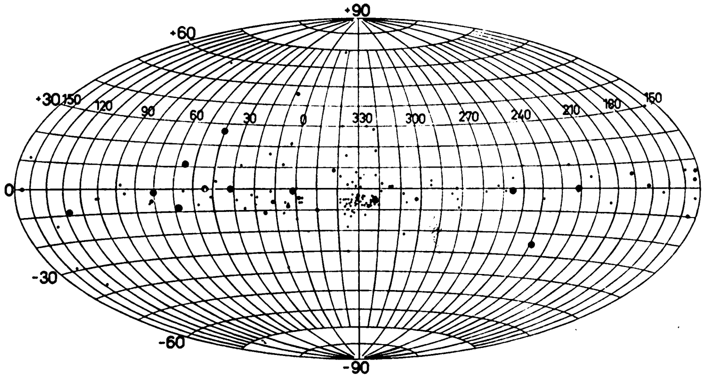

Fig. 7. Distribution of novae in galactic coordinates (from Payne-Gaposchkin, 1957).

(1957). In this case the similarity to the distribution of the known X-ray sources is indeed striking; the clustering in the Sagittarius region and also in the direction of Cygnus and the scarcity of both classes of objects between galactic longitude 150° and 250° is remarkable.

On the other side, until present, not a single X-ray source could be associated with

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a known nearby old nova. Clearly there are for this fact only two possible explanations.

Either strong X-ray emission is actually a general feature of a certain stage of the development of a nova, but this hypothetical 'X-ray stage' does not come immediately after the main outburst, but much later. Although not impossible, this explanation seems rather unlikely; if true our present ideas on novae should be considerably reviewed, especially considering the enormous power radiated by X-ray sources in the X-ray spectrum.

Or, alternatively, the majority of known X-ray sources, although superficially resembling an old nova in their photometric and spectral behaviour form a different class of objects (Mumford, 1967). This seems to me a much more likely possibility, which, however, leaves us where we were as far as the nature of X-ray sources is concerned.

There are of course other known objects having the same galactic distribution as old novae and, hence, as the X-ray sources. For instance, planetary nebulae (Payne-Gaposchkin, 1957) are very well known to have almost the same galactic distribution; nevertheless, according to Minkovski (1948), there is no direct relationship between planetary nebulae and novae.

I believe that the only reasonable conclusion which can be drawn from this kind of evidence is that the known X-ray sources, with a few exceptions, belong as galactic objects to an intermediate system, like novae and white dwarfs, but the physical and evolutionary implications of this fact are completely obscure.

This, however, rules out the possibility that among them there be a large proportion of Population II objects (spherical subsystems) and carts some doubts upon the interpretation of the large negative velocities observed in Sco X-1 and Cyg XR-2 as being the actual velocities of the centers of gravity of these objects, in agreement with Sofia and Wilson (1968) conclusion.

But, for the same reason, it seems to me very doubtful that a large percentage of the known X-ray sources might be true Population I objects connected with OB Associations as it was suggested by various authors (Braes and Hovenier 1966; Gursky *et al.*, 1967; Sofia and Wilson, 1968).

I will only mention, in passing, that some suggested identifications of X-ray sources with Wolf-Rayet stars (Vel XR-1 with ζ Pup or γ Vel, Lac XR-1 with HD 211853) have been either disproved or are very uncertain. If Wolf-Rayet stars possess any X-ray flux – and I do not see any reason why they should not – it is fainter than that corresponding to the limits of the present surveys.

The connection of X-ray sources with pulsars deserves a few more words. A recent discussion of this problem was published by Friedman *et al.* (1969), who point out that the distribution of pulsars in galactic coordinates (Figure 8) is very dissimilar from that of the X-ray sources; also the distances commonly accepted for pulsars do not fit with those of the X-ray sources.

Observations at 234, 256 and 405 MHz (Friedman *et al.*, 1969) have shown – I think – conclusively that the radioemission from Sco X-1 is not pulsed with periods in the range 0.1–5 sec.

A direct relationship of pulsars with *known* X-ray sources is thus extremely unlikely. Another (indirect) relationship may of course exist, since some X-ray sources are connected with supernova remnants and pulsars are now believed to be neutron stars formed following a supernova explosion. It is not unlikely, therefore, that at

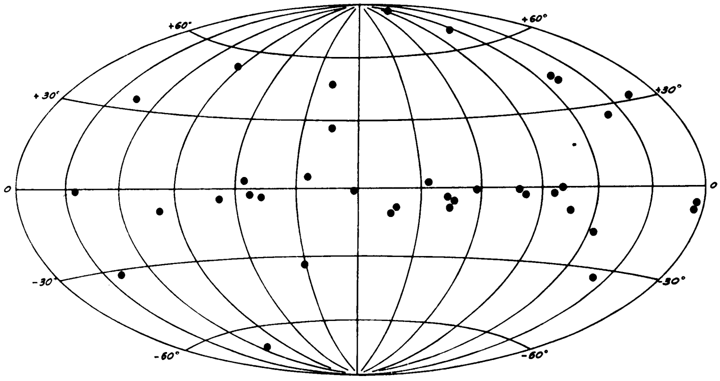

Fig. 8. Distribution of known pulsars in galactic coordinates (April 1969).

least one pulsar is nested in all supernova remnants and, conversely at a certain distance of all pulsars some remnants of the outburst are still lingering which might be found to emit X-rays.

A more direct relationship was also communicated for the first time in this symposium, that is the emission of pulsed X-rays by the pulsar itself. This is of enormous importance for the theory of pulsars, but I think that hardly anybody would maintain that the X-ray flux from Sco X-1 and similar sources could be of this type.

To conclude, I believe that we can safely risk the following statement which summarizes the situation: apart from a few objects which are clearly supernova remnants, *the vast majority of the known X-ray sources form a rather homogeneous class of objects which are members of an intermediate galactic subsystem, like novae and planetary nebulae*. The main characteristic of these objects is a very large ratio – from 10^3 to 10^4 – between the power emitted in the X-ray and optical spectra. In the optical range they are very similar to old novae with regard to light variations and spectroscopic behaviour; indeed were it not for the X-ray flux they would have been called old novae. If they are also close binary systems – which I do not think at present established – one of the components is a late type dwarf and the other a very high temperature object; in this case one should explain how a star can survive very close to an object from which it receives a quantity of energy of the same order or even larger than that produced by its own nuclear sources.

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