THE X-RAY SKY

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ABSTRACT Today X-ray astronomy encompasses almost all astronomical objects, from nearby stars to the most distant quasars. We review a few selected recent results obtained by X-ray astronomy on galactic objects like normal stars, supernova remnants, neutron stars and the black hole candidate Cyg X-1.

1. INTRODUCTION

Many of us are old enough to remember the Cosmic Ray Conferences in the mid sixties when X-ray astronomy could be reviewed in half an hour. Today this has become completely impossible - the X-ray sky comprises about a thousand sources representing almost all astronomical objects between nearby normal stars and the most distant quasars at the edge of the known universe. Therefore, I have to make a selection, and I have chosen a few topics of galactic X-ray astronomy which perhaps may be relevant to Cosmic Ray Origin. In particular, I will deal with normal stars, the chemical composition of supernova remnants, neutron stars and their magnetic fields and the question of stellar black holes.

As in any other branch of astronomy there are three major observational avenues in X-ray astronomy. Historically, studies of source variability have been most important and they will continue to play a major role because chaotic, periodic and quasi-periodic variability is characteristic of many sources. The large area detectors used for such studies also provide coarse spectral resolution. So far, high resolution spectroscopy with dispersive instruments and polarimetry have been used as powerful diagnostic tools only for a limited sample of bright objects. Recently, the power and beauty of imaging has become evident to a large community. The Einstein telescope with its much finer angular resolution and its one-thousand times greater sensitivity for point sources - compared with previous instruments - renders the first deep look at the X-ray sky.

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2. NORMAL STARS

One of the first surprises of the Einstein mission was the detection of OB associations as clusters of bright X-ray stars (Harnden et al., 1979). In the meantime a first survey of the sky has been completed which contains $\sim$ 140 objects of almost all spectral types and luminosity classes (Vaiana et al., 1980). Figure 1 summarizes the ratios of X-ray to optical fluxes measured for a number of main sequence stars. The distribution shows a rather large spread and a dramatic increase towards K stars, which radiate roughly one tenth of their energy in X-rays. For the late type stars a correlation between stellar X-ray flux and rotational velocities has been noted (Vaiana et al., 1980). Since our sun seems to be rather underluminous in X-rays, previous predictions for stellar coronal X-ray fluxes have been too pessimistic.

For giants and supergiants of spectral types between O and K the ratio of X-ray to optical luminosities is similar to that of main sequence stars. However, in the case of late type giants only upper limits of the X-ray fluxes could be detected indicating a drastic decrease of f_X/f_O for cool giants. This is a rather dramatic effect indeed. For α Sco, a M1 supergiant, the mean X-ray flux at the stellar surface is more than a hundred times lower compared with that of solar coronal holes (Vaiana et al., 1980).

Clearly all these new results have a great impact on our notion of stellar coronae, their heating and their confinement, as well as on the physics of stellar winds and their interaction with the interstellar medium. They also can be relevant for the origin of cosmic rays, at least those of rather low energies.

3. CHEMICAL COMPOSITION OF YOUNG SUPERNOVA REMNANTS

Supernova remnants are bright X-ray sources and belong to the classical objects in X-ray astronomy. In general, the X-ray emission of supernova remnants comes from a mixture of ejected stellar and shocked interstellar material. In sufficiently young supernova remnants the contribution of the ejected component may not be negligible, opening the possibility to observe freshly synthesized material. Figure 2 shows the Einstein observatory high resolution imager picture of Cas A, the youngest known galactic supernova remnant (Murray et al., 1979). The brightest parts of this shell source are at a temperature of $\sim 10^7$ K. The faint halo which can be seen just outside the bright emission region may be produced by the shock wave moving ahead of the expanding debris.

The chemical composition of the glowing material can be deduced from the spectra obtained with the Einstein solid state spectrometer as shown in Fig. 3 (Becker et al., 1979 a). The data suggests a strong enhancement of elements between silicon and calcium but nearly normal iron abundance, compared with the solar composition. Similar results

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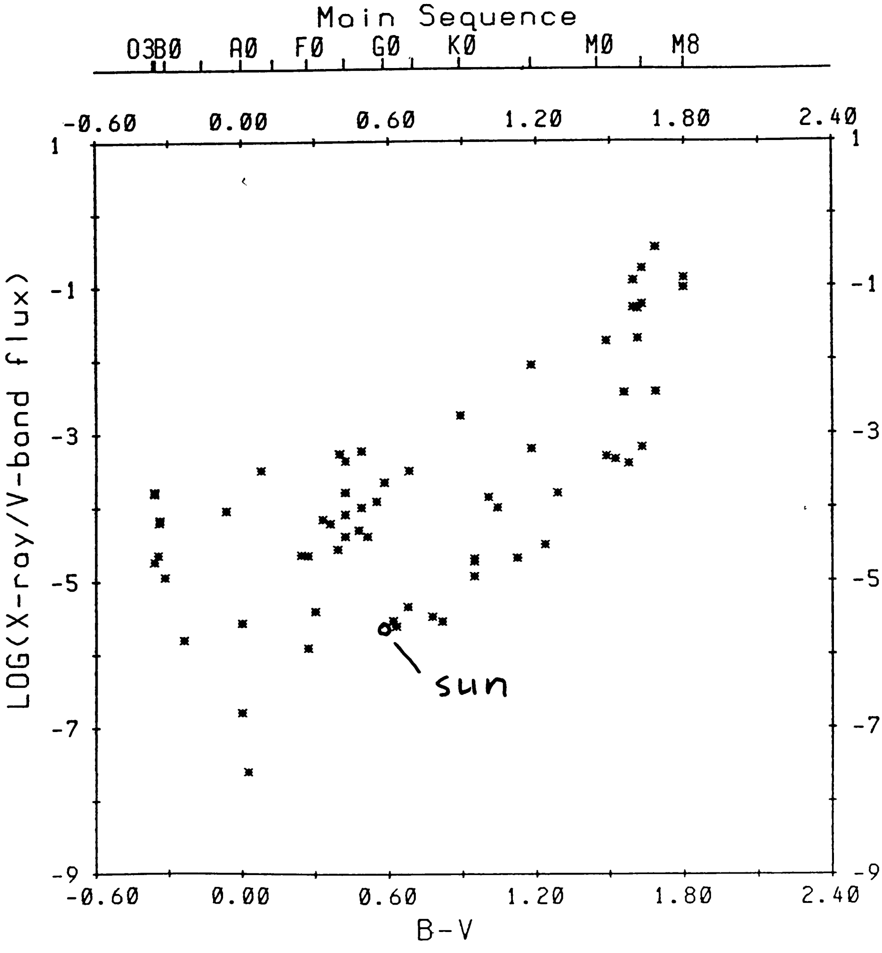

Figure 1. The ratio of soft X-ray to V-band fluxes for main sequence stars detected in the Einstein stellar survey (from Vaiana et al., 1980; the solar point has been added by the present author).

have been obtained for the Kepler and Tycho supernova remnants (Becker et al., 1979 b; Becker et al., 1980).

4. NEUTRON STARS

X-ray emitting neutron stars have been probably found in four different astrophysical situations:

(1) The Crab pulsar remains a unique object. Obviously its pulsed X-ray emission is part of the non-thermal radiation emitted synchronously

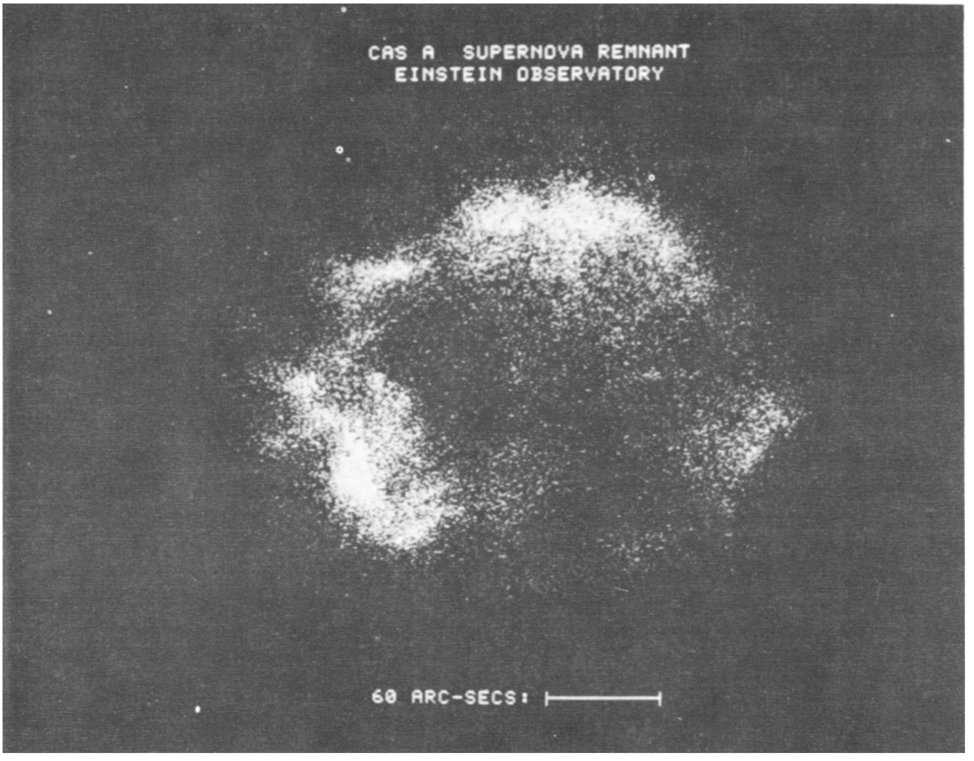

Figure 2. X-ray image of the Cas A supernova remnant, obtained with the Einstein high resolution imager (from Murray et al., 1979).

at all frequencies between radio waves and gamma rays.

(2) The large sensitivity of the Einstein observatory has made it possible to look for thermal emission from the surface of isolated neutron stars. An extensive survey of radio pulsars and supernova remnants has led to a number of upper limits on the surface temperature (Helfand et al., 1980). Of course the Crab pulsar as the youngest of the known pulsars is of particular interest. A limit on the temperature of 3×10^6 K had been obtained by lunar occultations (Toor et al., 1977) which may be improved by the final analysis of the data obtained with the Einstein high resolution imager. Another candidate is the Vela pulsar. Einstein observations have revealed the presence of an extended ($\sim$ 1 arcmin) diffuse source around the Vela pulsar which may be a Crab nebula type object. At the center a point like feature has been found which could be attributed to thermal emission of the neutron star. The corresponding black body temperature is then $\sim 1.5 \times 10^6$ K (Harnden et al., 1979).

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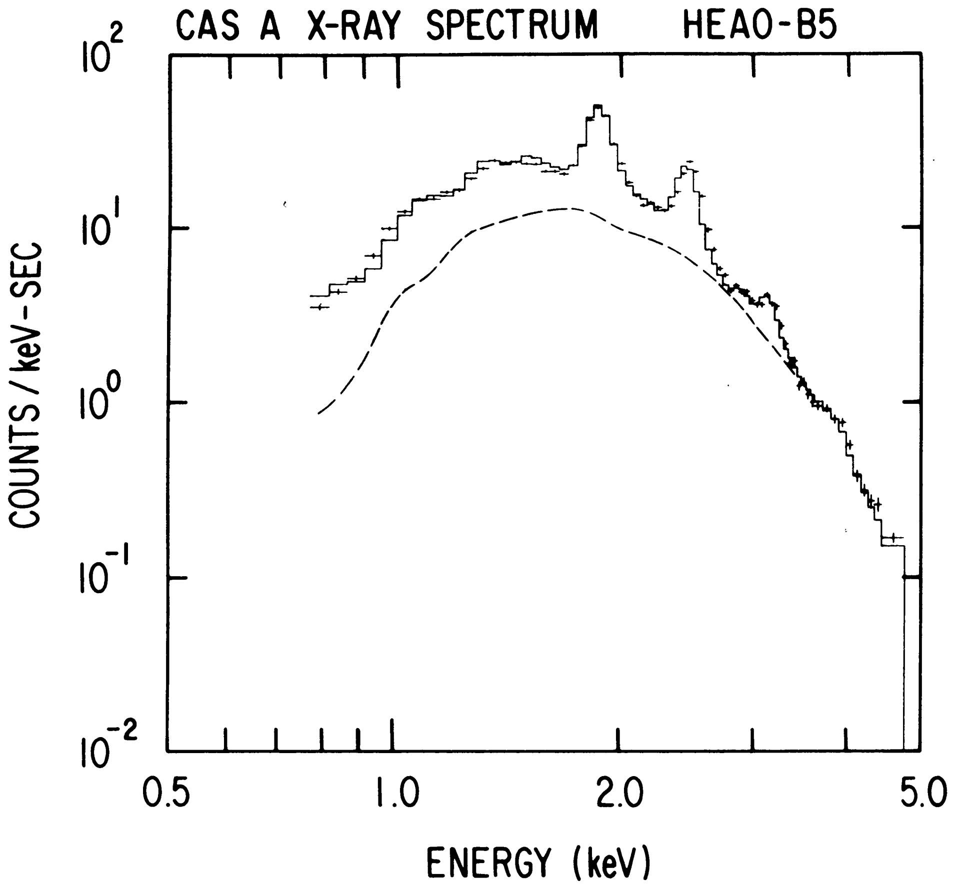

Figure 3. X-Ray spectrum of the Cas A supernova remnant, obtained with the Einstein solid state spectrometer. The dominant line features are due to emission from helium-like silicon and sulfur ions (from Becker et al., 1979 a).

Recently a third case has been reported by Tuohy et al. (1980), who find a point source in the supernova remnant RCW 103. If it is a neutron star, its black body temperature is ~ 2.1 x 10^2 K. Figure 4 shows a compilation of these data and several other upper limits in comparison with theoretical cooling curves of neutron stars (after Tsuruta, 1979). For most cases the data are consistent with the predictions of standard cooling models. The upper limits for Tycho SNR and SN 1006 suggest that these objects either do not contain a neutron star or cooling is much faster, e.g. due to neutrino emission of a pion condensate.

(3) About 25 X-ray bursters are known which form a galactic bulge popu-

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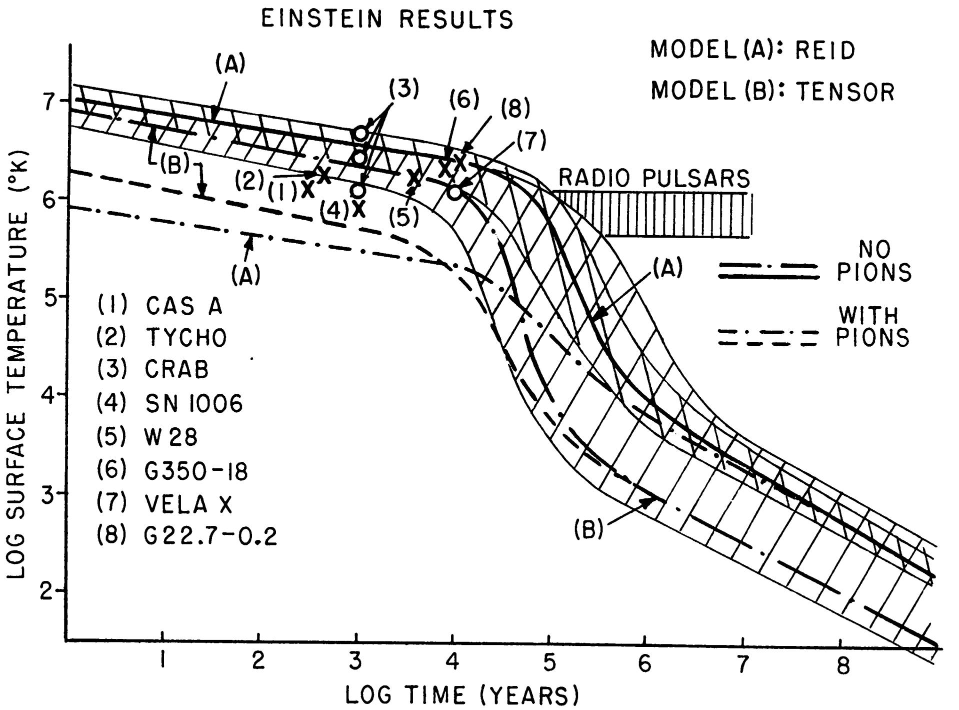

Figure 4. Comparison between surface temperatures predicted from theoretical work and preliminary results from the Einstein observatory (Tsuruta, 1979). The shaded stripes represent surface temperatures expected for a range of masses, magnetic fields and neutron star models, without effects of a pion condensate on cooling. The latter effects lead to the dashed curves.

lation, and a few of these objects are found in globular clusters (e.g. Lewin and Clark, 1979). There is good evidence that bursters represent weakly or non-magnetized neutron stars in binary systems with low mass companions ($\lesssim 0.3\ M_\odot$). The bursts are probably a result of thermonuclear explosions of accreted material (He-explosions) piled up at the neutron star surface as first suggested by Maraschi and Cavaliere (1977), and worked out in more detail by Joss (1978). The burst spectra are of black body type showing a temperature decrease during the bursts. The 'black body radii' of the objects are of the order ~ 10 km, consistent with neutron star dimensions (Hoffmann et al., 1977; von Paradijs, 1978).

(4) The classical pulsating X-ray sources like Cen X-3 and Her X-1 have provided a wealth of information on neutron stars. There are now

some 18 objects known with periods ranging from 0.7 to 835 seconds (cf the review of Rappaport (1979) and recent results by Lamb et al. (1980) and Kelley et al. (1980)). For most of them the binary nature has been well established and the companion masses range from ~ 2 $M_\odot$ to ~ 30 $M_\odot$. They are powered by gravitational energy release of the accreting matter and the occurence of X-ray pulsations suggests an efficient magnetic channelling ($B \gtrsim 10^{11}$ G) of plasma flow onto the neutron star's polar caps. The X-radiating spot must have rather small dimensions (~ 1 km).

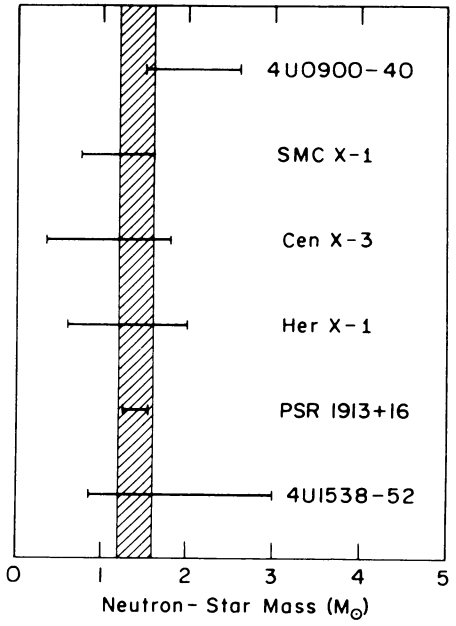

Figure 5. Empirical knowledge of neutron star masses (from Rappaport and Joss, 1979). PSR 1913+16 is the binary radio pulsar. The other masses are derived from observations of X-ray binaries.

Pulse timing measurements have been used to determine the orbital parameters of several of these systems and to derive neutron star masses (Rappaport, 1979). Figure 5 shows that all observations are consistent with a typical neutron star mass of 1.3 - 1.4 $M_\odot$, in good agreement with theoretical expectations. In contrast to radio pulsars, pulsating X-ray sources generally show a spin-up which is obviously a result of momentum transfer to the neutron star by the accreting matter. In addition, erratic period changes have been observed in several sources, notably in Her X-1 and Vela X-1, which may be due to fluctuations in the accretion rate or to intrinsic torques (cf Boynton et al., 1979).

5. MAGNETIC FIELDS OF NEUTRON STARS

Already before the discovery of radio pulsars it had been suggested that neutron stars possess very strong magnetic fields ($B \sim 10^{12}$ G) due to magnetic flux conservation during the gravitational collapse (Woltjer, 1964; Pacini, 1967).

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This order of magnitude estimate has been confirmed by observations of radio pulsars: The spin-down of these objects - interpreted as a consequence of magnetic braking - leads to magnetic moments of the order of 10^{30} Gauss cm^3, corresponding to surface field strengths of $\sim 10^{12}$ Gauss. A further estimate can be obtained from the spin-up of pulsating X-ray sources which is due to the transfer of angular momentum onto the neutron star by the accreting matter. The expected period change $\dot{P}$ depends on the mass accretion rate $\dot{M}$ (derived from the X-ray luminosity L), the magnetic moment of the neutron star μ, its moment of inertia I, and the details of the interaction between the stellar wind/accretion disk and the rotating magnetosphere (Pringle and Rees, 1972; Lamb et al., 1973; Gosh and Lamb, 1979; Anzer and Börner, 1980). Under a wide range of conditions one expects a dependence

$$\dot{P} \sim \mu^{2/7} \quad R^{6/7} \quad M^{-3/7} \quad I^{-1} \quad (PL^{3/7})^2$$

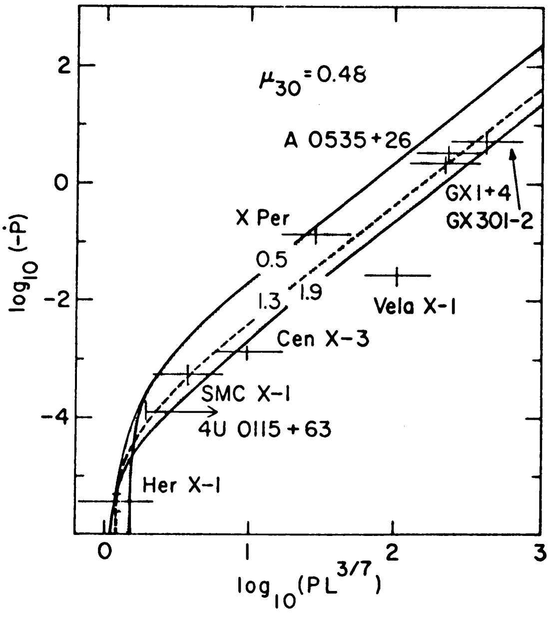

Figure 6. Relation between spin-up rate $\dot{P}$ and X-ray luminosity L predicted by disk accretion theory. Superimposed are the data of nine pulsating X-ray sources (from Lamb, 1979).

Figure 6 shows that the pulsating X-ray sources as a class indeed behave as expected for standard magnetic neutron stars with a magnetic moment of $\sim 10^{30}$ G cm^3, in good agreement with the other estimates. Of course, these cannot be more accurate than to an order of magnitude, since the very details of the braking and spin-up mechanisms as well as the radii and moments of inertia of neutron stars are poorly known.

A rather direct determination of neutron star magnetic fields may be obtained by cyclotron line spectroscopy of pulsating X-ray sources. Figure 7 depicts the hard X-ray spectrum of the Her X-1 1.24 sec pulses which shows strong structures above 40 keV (Trümper et al., 1977, 1978, 1979). It can be seen easily that for abundance reasons atomic or nuclear lines cannot be responsible for these features.
On the other hand, electrons

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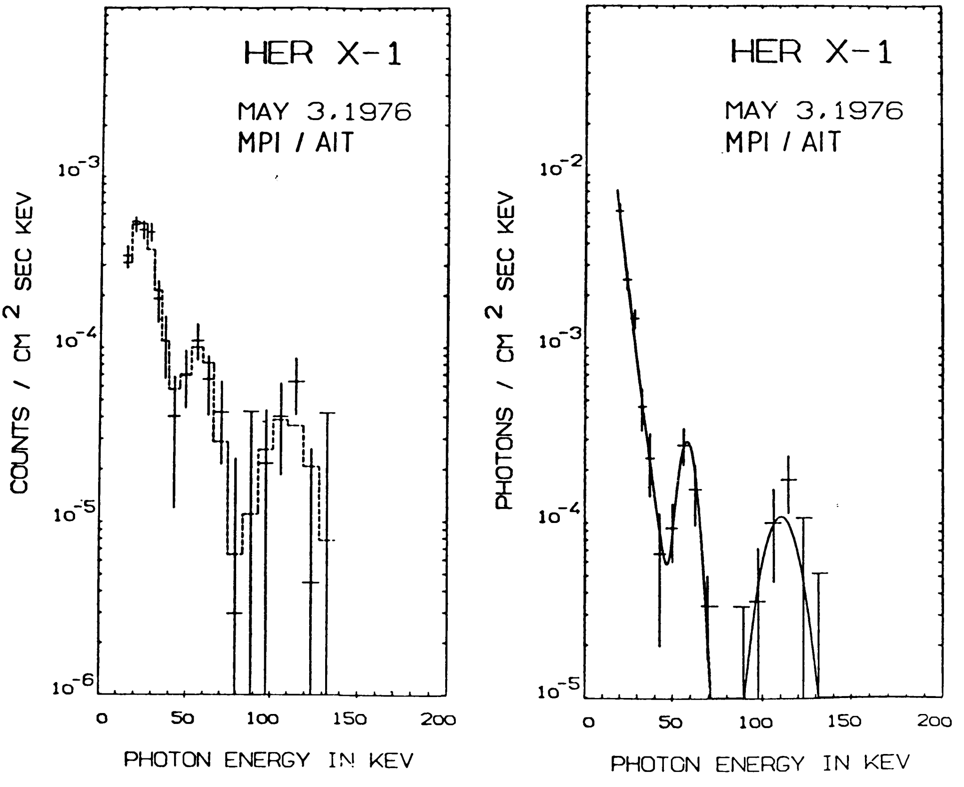

Figure 7. Hard X-ray spectrum of Hercules X-1 obtained during the pulse phase of the 1.24 sec pulsations. The left diagram shows raw count rate spectra. The other diagram shows the deconvoluted spectrum, assuming spectral lines at 58 keV and 110 keV (from Trümper, 1979).

are the most abundant species in the radiating polar hot spot and their (transverse) energies are quantized in units of the cyclotron frequency

$$\hbar\omega_B = \hbar \frac{eB}{mc}.$$

The corresponding Landau transitions may show up in the spectrum as emission or absorption lines depending on the details of the density and temperature distributions in the outer layers of the emitting plasma (Trümper, 1979). For Her X-1 one finds surface magnetic field strengths of $\sim 5.3 \times 10^{12}$ G (emission line) or $\sim 4 \times 10^{12}$ G (absorption line), which need to be corrected for the unknown gravitational red shift (15-30 %) of the neutron star.

It should be noted that the detection of cyclotron resonances requires that the magnetic field is sufficiently homogeneous over the emission region. In the present case $\Delta B/B \leqslant .3$ which means that for a dipole configuration the radial extent of the emission region is less than a tenth of the neutron star radius, i.e. $\leqslant 1$ km in agreement with 'black body' estimates of the radiating surface (Trümper et al., 1978).

While the existence of the feature at ~ 58 keV has been confirmed by later balloon (Voges et al., 1979) and HEAO-1 (Gruber et al., 1978) observations, the second harmonic line has not been seen again. This may be explained by smaller source luminosities (and temperatures) in the later observations. Recently, similar features have been found in 4U 0115+63 ($P = 3.6$ s; $B \sim 2 \times 10^{12}$ G, Wheaton et al., 1979) and possibly in 4U 1626-67 ($P = 7.7$ s ; $B \sim 2 \times 10^{12}$ G, Pravdo et al., 1979).

6. STELLAR BLACK HOLES

The question of the existence of stellar black holes is one of the most important issues of modern astronomy, but despite of many attempts there has been embarrassingly little real progress in this context. The present evidence still rests mainly on the few compact sources with strong variability and apparently large masses among which Cyg X-1 is the clearest case (cf Eardly et al., 1978). However, the mass argument is not irrefutable and rapid variability is also seen in the case of neutron stars. The hopes to establish the black hole nature of globular cluster X-ray sources have not materialized so far. The deviations of X-ray source positions from the cluster centers obtained by Einstein high resolution measurements lead to masses of the sources of $M_X \geq 2\ M_\odot$ ($2\ \sigma$). Since M_X includes the mass of a likely present low mass companion the result is consistent with normal neutron star binaries (Grindlay, 1979).

In the case of Cyg X-1, also spectroscopic data have been used to support the black hole evidence. Figure 8 shows the hard X-ray spectrum measured with high precision by Voges et al. (1980). It can be fitted very well by the spectrum expected from Comptonization of soft photons in a hot plasma cloud which is at a temperature of $kT \sim 27$ keV with a Thomson optical thickness of $\tau = 5$ (Sunyaev and Trümper, 1979). Such comptonizing plasma clouds are an integral part of models describing disk accretion onto black holes. While the outer disk is cool (Pringle and Rees, 1972), it becomes unstable and hot in the vicinity of the black hole. In this hot inner part of the disk free-free radiation processes are rather inefficient and Comptonization of soft photons in the hot plasma becomes the main cooling process leading to hard X-ray spectra as observed in Cyg X-1. Interpreting the observed spectrum in terms of this model it is possible to obtain some important parameters of the disk. Apart from the temperature ($kT \sim 27$ keV) and luminosity ($L_X = 10^{37}$ erg/sec) which are directly measured one can derive the radial inward velocity of matter in the disk ($v \sim 10^{-2}$ c) and the turbulence parameter ($\alpha \sim 1$) (Sunyaev and Trümper, 1980). Of course, this

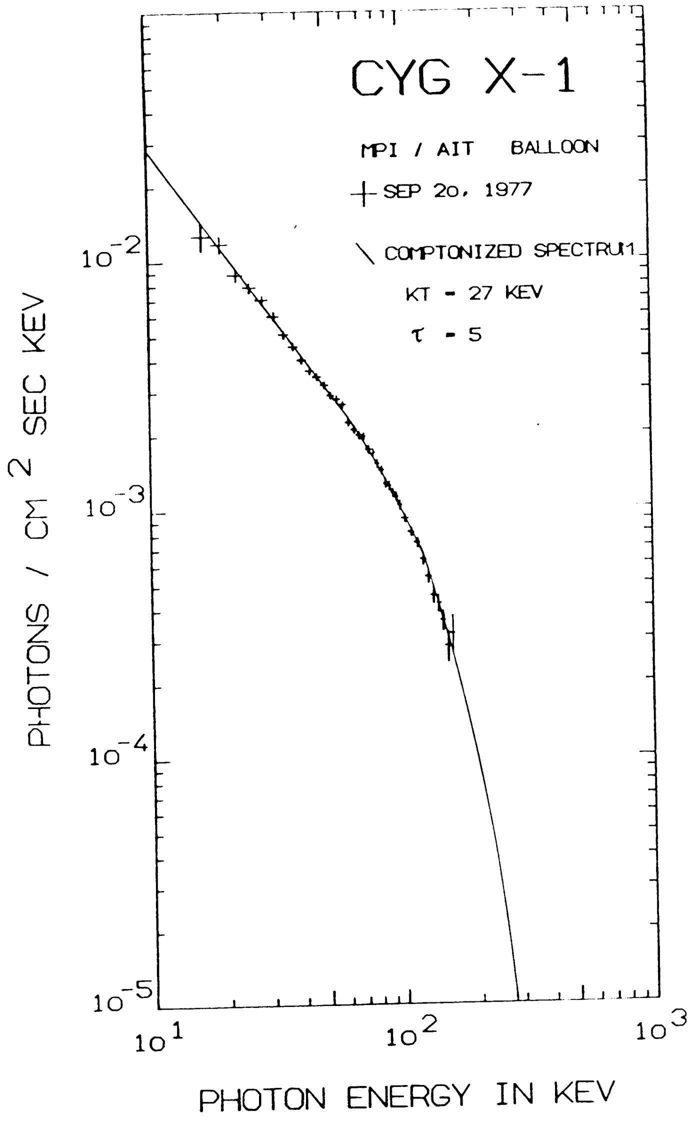

Figure 8. Hard X-ray spectrum of Cyg X-1, observed by the MPI/AIT balloon experiment. The solid line represents a photon spectrum expected from Comptonization of soft photons in an electron cloud with a temperature of 2.5×10^8 K and a Thomson optical thickness $\tau=5$ (from Sunyaev and Trümper, 1979).

does not proof the black hole nature of Cyg X-1, but is one more piece of indirect evidence.

7. FINAL REMARKS

Although many surprising discoveries and a wealth of quantitative information has been obtained by galactic X-ray astronomy, we are still at the beginning of the development of this field. As usual in new and rapidly developing fields, there are now more questions than before. We can be sure, that further progress will come from Einstein observations. We can also hope that the upcoming, powerful X-ray missions now in preparation will answer many of the present questions. They may also help to solve one of the most important problems of astrophysics: the question of the Origin of Cosmic Rays.

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