Reports

Energy Spectra of a Number of Celestial X-Ray Sources in the Energy Range from 2 to 60 Kiloelectron Volts

Abstract. *The emission of 20 to 60 kev x-rays by an astronomical object in the constellation of Cygnus has been observed with a balloon-borne x-ray telescope flown from Hyderabad, India. The balloon data, used in conjunction with data pertaining to the flux in the wavelength range from 2 to 10 Å can be fitted by a power law in photon energy varying as* $(h\nu)^{-1.7}$. *The Cygnus object is the brightest object in the sky in the hard x-ray wavelength range and has the hardest spectrum of all observed objects that emit x-rays. The astronomical object should be capable of accelerating protons up to energies of the order of* 10^{18} *electron volts. Upper limits to the hard x-ray fluxes from Sco XR-1, Cyg XR-2, Oph XR-1, and Ser XR-1 are established; it is shown that the Sco XR-1 spectrum is very soft.*

To date, some ten x-ray objects have been uniquely identified in the sky observable from the Northern Hemisphere *(1, 2)*. The spectra of the x-rays emitted by two of these objects, Taurus A and Cygnus XR-1, have been studied over the energy range 2 to 60 kev *(3, 4, 5)* wavelength (λ = 0.2 to 6 Å), the spectra having been reported previously to be quite similar *(4)*. The Taurus source has been identified with the Crab nebula (Taurus A), a supernova remnant, and various investigators have suggested that the x-ray emission is due to synchrotron emission by relativistic electrons in the magnetic fields within the supernova remnant. The observation of a power law spectrum between 2 to 100 kev *(5)* supports such a view. Of the remaining celestial x-ray sources, one has been observed close to the radio object Cassiopeia A *(6)*, believed to be the remnant of a supernova which occurred about A.D. 1700, while another, Ophiuchus XR-1 *(1)*, is close to the position of Kepler's supernova of A.D. 1604. There is reason to believe, therefore, that x-ray and radio emission may be commonly generated within supernovae remnants and that both emissions are due to the synchrotron emission of relativistic electrons.

Of all observed sources, the Scorpius x-ray source is the most intense in the energy range 1.5 to 6 kev; therefore, in 1964, a balloon-borne experiment was designed to search for x-rays from this object in the energy range 20 to 60 kev. To minimize the background from the charged cosmic radiation, the experiment was flown from Hyderabad, India (vertical cut-off rigidity $\approx$ 16.9 Bev) during March and April 1965, as part of the IQSY (International Year of the Quiet Sun) balloon-flying expedition (EQEX). The portions *(4)* of the celestial sphere scanned during the two flights contained the known x-ray sources Cygnus XR-1 and XR-2, Serpens XR-1, Ophiuchus XR-1, and Scorpius XR-1. The observation of x-rays from the constellation of Cygnus during flight Hyd-2 has been reported elsewhere *(4)*; however, I have reexamined this observation in the light of more recent measurements of the x-ray spectrum from 2 to 8 Å. Now I report the results of the two Indian flights insofar as x-ray emission by the other known sources is concerned and show that, of all sources, the Cygnus source has the hardest spectrum, the spectrum being consistent with a synchrotron radiation origin. By contrast, the Scorpius XR-1 source exhibits a radically different, soft spectrum, which is indicative of bremsstrahlung from a thin, hot plasma.

The balloon-borne detector is summarized in Fig. 1. The basic detector is a thick (1.25 cm) NaI (Tl) scintillator, of diameter 17.5 cm, viewed by a 17.5-cm photomultiplier which is shielded over its whole length by a "conetic" magnetic shield. The "radiation window" of the x-ray telescope consists of 0.2 g cm^{-2} of polyurethane, 0.27 g cm^{-2} of Al, and 0.07 g cm^{-2} of MgO. The cone of acceptance of the detector is defined by a set of 1/32 inch (0.08 cm) brass plates, which present a minimum absorption of 9 $\times$ for any photon in the energy range of 20 to 60 kev which passes through them. For most paths, the attenuation is greater by a factor of ten or more, and hence the detector has a well-defined "fan beam" cone of acceptance. The effective cross-section of the device for the detection of x-rays is illustrated in Fig. 1 (bottom), the full-width half maximum (FWHM) of the detector in the plane normal to the collimator being 19°.

The photomultiplier-crystal combination was observed to have a FWHM line width of 42 percent for the 30 kev x-rays of Ba^{133}. In the flight equipment, the photomultiplier pulses were analyzed by a pulse-height analyzer providing five contiguous differential channels between 20 and 58 kev, and an integral channel of more than 58 kev. The experiment was connected to the balloon by a "line twister" which caused the experimental package to rotate with a period of about 11.2 minutes. The method of suspension was such that the viewing axis of the x-ray detector made an angle of 22° with the vertical, the fan beam passing through the zenith. Thus, as the instrument was rotated by the line twister, the x-ray telescope scanned a small circle on the celestial sphere, the full-width half maximum width of the detector, in terms of azimuthal rotation of the detector, being (19°/sin θ) degrees, where θ is the zenith angle of the celestial x-ray source. A single-axis Schonstedt flux-gate magnetometer provided azimuth information; the accuracy of this instrument is $\pm$ 3° or better.

For each flight, the data for average azimuth and counting rate have been determined for every 10.5-second interval throughout the flight. The flights were then divided into 90-minute segments; the average counting rate for each 10°-interval of magnetic azimuth was determined for each segment and for each window of the pulse-height analyzer.

The two successful flights, Hyd-2 and Hyd-3, were made on 2 April 1965 and 8 April 1965, respectively; the same instrument was flown on both occasions. In both flights, the balloons floated at a constant atmospheric depth of 4.5 g cm^{-2}. The former flight reached its floating altitude about 1 hour after the meridian transit of Cygnus A, while the latter flight reached its float altitude concurrently with the meridian transit of Scorpius XR-1.

In the lower curve of Fig. 2, a well-defined peak is centered on an azimuth of 34°W. The azimuths of both Cygnus A and XR-1 (*1*) at this time are indicated. At this time, the mean positions of these celestial objects were 30° from the zenith; Fig. 1 indicates that the azimuthal variation of counting rate based on the assumption of a point source of x-rays at this zenith angle is a triangular wave of FWHM 36°. The similarity of the observed counting rate variation with azimuth and the theoretical curve suggests that the peak in Fig. 2 is due to x-rays from the general vicinity of Cygnus A or XR-1.

Comparison of the two curves in Fig. 2 shows that the peak in the curve corresponding to the period 1000 to 1130 IST is less pronounced than that for the period 0830 to 1000 and that it is shifted towards the west. Comparison of the excess fluxes under the peaks shows that the flux at the later time is 0.68 ± 0.12 of that at the earlier time, while the mean position of the peak has shifted 16° to the west. For an assumed x-ray source in the direction of Cygnus XR-1 the mean atmospheric thickness differs between the two periods by 0.9 g cm^{-2}, and the average attenuation factor for such a thickness of air for a flat spectrum in the range 26 to 45 kev is 0.75; the attenuation factor approaching a limiting value of 0.65 as the spectrum steepens. The diurnal rotation of the earth caused the average azimuth of Cygnus XR-1 to move 11° to the west between the times noted. The quantitative agreement between the observed and the predicted attenuation and the westward shift of the peak supports the hypothesis that the peaks are due to an x-ray flux from the general direction of Cygnus.

During April 1965, a rocket-borne instrument made a detailed survey of the celestial x-ray objects in and near the constellation of Cygnus in the wavelength range from 2 to 10 Å (*6*). This flight indicated that the x-ray object originally named Cygnus XR-1 probably consisted of two sources which were of roughly equal intensity in April 1965, one being Cygnus XR-1 and the other being coincident with the radio-emission object Cygnus A. From Fig. 2 it is clear that the balloon-borne experiment was of insufficient resolution to separate these two objects, and consequently the following discussion pertains to the composite of the two sources which is referred to as Cyg (XR-1 + A).

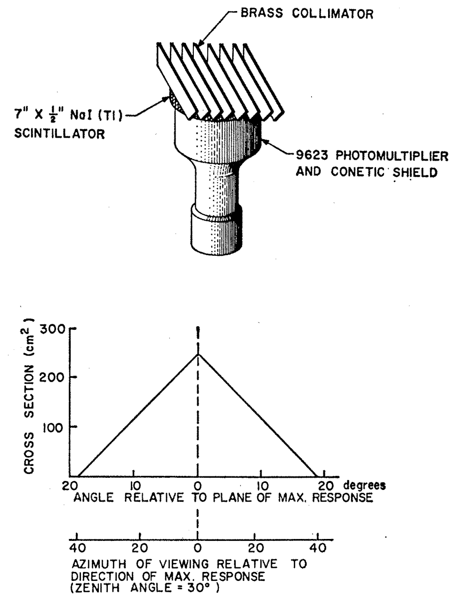

Fig. 1. (Top) The configuration of the scintillator, photomultiplier, and mechanical collimator which constitute the x-ray detector; (bottom) the detector cross-section area as a function of viewing angle.

If, as a first approximation, a differential photon energy spectrum varies as $(h\nu)^{-2}$, the counting-rate increment evident in Fig. 2 yields a photon flux of (5.7 ± 0.6) × 10^{-3} photons cm^{-2} sec^{-1} kev^{-1} at a mean energy of 35 kev after allowance has been made for atmospheric absorption. This flux value,

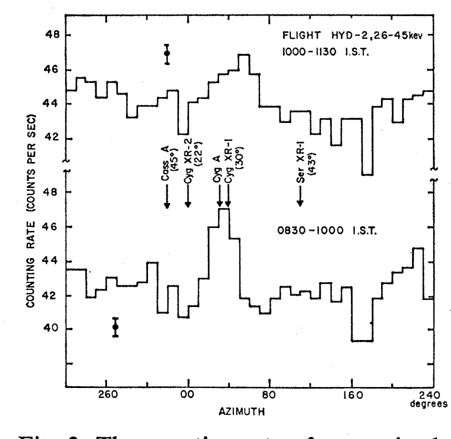

Fig. 2. The counting rate of x-rays in the energy range of 26 to 45 kev as a function of geomagnetic azimuth, measured westward from geomagnetic north for flight Hyd-2. The azimuth of a number of known x-ray sources are indicated, their zenith angles being given in the brackets.

plus that derived from the rocket measurements, yields a new estimate of the exponent of the energy spectrum, and this new value was used to recalculate the photon flux with the data displayed in Fig. 2. Reiteration, in this fashion, leads to a photon flux of (5.8 ± 0.6) × 10^{-3} cm^{-2} sec^{-1} kev^{-1} at a mean energy of 35 kev derived from the balloon data. This flux, plus the Cygnus A and Cygnus XR-1 fluxes of the NRL (Naval Research Laboratory) group for April 1965, lead to the spectrum shown in Fig. 3, the spectral exponent of a power-law fit to the Cygnus data being −1.70. The spectrum of Taurus A, as derived from rocket (*1*) and balloon (*5*) measurements is also shown in Fig. 3. Other balloon measurements (*3*) indicate an even steeper spectrum for Taurus A. Thus the Cyg (XR-1 + A) spectrum is significantly harder than that of Tau A.

The data from flight Hyd-3 indicate that there was no statistically significant change in counting rate as the detector scanned across Sco XR-1. If a two-standard-deviation flux increment is taken as an estimate of the maximum x-ray flux which may have been present from Sco XR-1, and, after due allowance is made for atmospheric absorption, an upper limit to the Sco XR-1 flux can be made corresponding to any assumed spectral shape. Two radically different spectra have been used to calculate the upper limits appropriate to Sco XR-1, these being (i) a power law in energy, E^{-2}; and (ii) a bremsstrahlung spectrum E^{-1} exp $(-E/E_p)$, where $E_p = 5.0$ kev. These limits are displayed in Fig. 3, along with the data obtained at lower energies by other workers.

It is immediately evident that, whereas the Cygnus and Taurus objects exhibit basically similar spectra over the 2- to 60-kev energy range, the spectra of Sco XR-1 is markedly different. Thus, while the Taurus and Cygnus spectral data are suggestive of power laws in energy with exponents in the vicinity of −2, the Scorpius spectrum is much steeper. Chodil *et al.* (*7*) have suggested a spectral form of AE^{-1} exp $(-E/E_p)$, the spectrum appropriate to the bremsstrahlung radiation from a thin, hot plasma, with a Maxwellian energy distribution centered at $E_p = 5.0$ kev.

The Hyderabad balloon data are certainly consistent with such a spectrum up to 60 kev. The possibility that the Sco XR-1 spectrum might be a com-

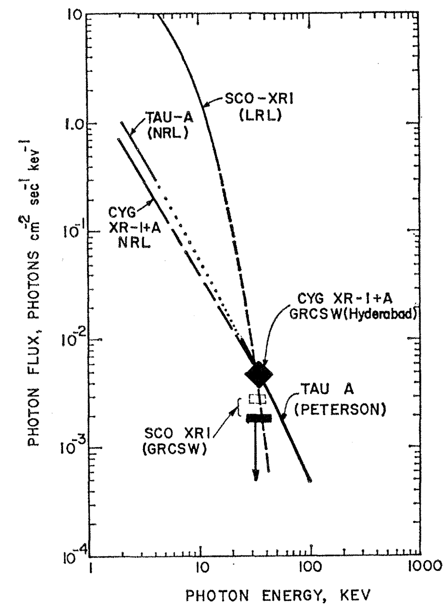

Fig. 3. The spectra of the Cygnus composite, Taurus A, and Scorpius XR-1, as deduced from previous measurements, and the balloon data reported here.

posite of a 5.0-kev thermal bremsstrahlung spectrum and a synchrotron radiation spectrum of spectral exponent -2 is limited to the case in which the synchrotron radiation at 2 kev is less than 5.9×10^{-3} of that due to the thermal bremsstrahlung.

Throughout the course of the two balloon flights, various other x-ray objects were scanned by the x-ray telescope. In no case was a significant x-ray flux detected, and upper limits to the x-ray flux in the energy range of 26 to 45 kev have been computed as in the case of the Sco XR-1 source. These upper limits are 1.5×10^{-3} photons cm^{-2} sec^{-1} kev^{-1} for Cyg XR-2, 3.0 $\times 10^{-3}$ for Ser XR-1, and 2.0×10^{-3} for Oph XR-1, where all fluxes refer to a mean energy of 35 kev.

So far, the rocket observations indicate that celestial x-ray sources are largely confined to the galactic disc, being concentrated near the galactic center. This distribution is similar to that of the stars and supernovae within our galaxy, and therefore it indicates that the majority of the x-ray objects seen up to now are galactic.

The Hyderabad balloon flights surveyed the whole of the galactic disc from the vicinity of the galactic center to the vicinity of Cassiopeia A, a region containing roughly half of the known x-ray objects. The Cygnus composite (Cyg XR-1 + Cyg A) was the only x-ray object visible in the 20 to 60 kev energy range over this whole section of the celestial sphere, and it is therefore clearly one of the brightest, if not the brightest, x-ray object in the sky at these energies. If the Cygnus spectrum in Fig. 3 is used, the energy flux at the earth between 1 and 60 kev, due to the Cygnus composite is computed to be 2.6×10^{-8} erg cm^{-2} sec^{-1}. By comparison we note that Cygnus A emits 10^{-10} erg cm^{-2} sec^{-1} between 22 and 3000 Mcy/sec (*8*). That is, in terms of total energy flux, the emissions at x-ray energies of certain classes of celestial bodies are dominant.

The power-law energy spectrum of the Cygnus composite is suggestive of a synchrotron radiation origin for the x-ray emissions. To radiate at a frequency of ν by synchrotron emission, the electron energy (in ev) and magnetic field strength (H) (in oersteds) are related by $E^2H\perp \simeq 2.21 \times 10^5\ \nu$, and the time scale for the electrons to lose half their energy, and hence radiate photons of energy one quarter of the initial value, is $\tau \approx 4 \times 10^{14}H^{-2}E^{-1}$ seconds. Hence to generate 40 kev photons ($\nu = 10^{19}$ cy/sec), $E^2H\perp \approx 2.21 \times 10^{24}$. If $H\perp$ is about 1 oersted (*9*), then E is about 1.5×10^{12} ev, and $\tau \approx 2.7 \times 10^2$ seconds. Therefore, in order to radiate 40 kev photons, a substantial population of very high energy electrons would be required, and their lifetimes would be very short. If the emission is in equilibrium with the acceleration of relativistic electrons, this implies a continuous energy input of in excess of $3.25 \times 10^{-7} \times R^2$ erg sec^{-1} into relativistic electrons in the celestial object, which is assumed to be at a distance R cm from earth. If only half of the energy flux from the Cygnus composite were due to Cygnus A (*6*), this would imply continuous investment of 1.17×10^{46} erg sec^{-1} into the relativistic electron spectrum. Over a year this amounts to 3.5×10^{53} erg; that is, about 10^{-6} of the total kinetic energy computed for the visual object associated with Cygnus A (*8*). Furthermore, to accelerate an electron to an energy in excess of 10^{12} ev requires an energy input rate in excess of the synchrotron radiation loss rate. For a field of 1 oersted, and an electron of 10^{12} ev, this implies an energy investment rate of 4×10^9 ev/sec per electron in order that the electron spectrum in the vicinity of 10^{12} be maintained. Both this high rate of energy input to a single electron and the large amount of energy stored in the relativistic electron population imply a very efficient mechanism for the acceleration of electrons to energies in the vicinity of 10^{12} ev. The mechanism would likewise be effective in the acceleration of protons, the absence of synchrotron radiation (at $E < 10^{22}$ ev) implying that the acceleration mechanism would be capable of accelerating protons to energies far in excess of 10^{12} ev, the limiting energy for protons being set by the energy at which they escape from the accelerator. Since the gyroradius of even a 10^{18} ev proton in a 1-oersted field is 10^{-3} parsec (approximately 200 astronomical units), this being a small distance on a cosmic scale, acceleration may well continue up to such energies before escape occurs. Of all x-ray sources, the Cygnus composite would therefore appear to be the one containing the most effective acceleration mechanism, and consequently the highest energy protons. The Cygnus composite, and similar objects, would therefore appear to be capable of providing an explanation for the existence of cosmic rays of about 10^{18} ev in the universe without the added requirement of acceleration within interstellar space.

It is also worthy of note that the Scorpius XR-1 object is clearly radically different in physical nature from either Tau XR-1 or Cyg (XR-1 + A), the spectrum suggesting that there are few relativistic electrons trapped within the x-ray object. This probably excludes a supernova remnant as the source of the x-radiation.

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References and Notes

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9. Throughout this discussion a value of 1 oersted is assumed to be characteristic of the magnetic fields within the astronomical object of interest. Changing the assumed value over the range 10^{-2} to 10^2 oersted does not affect the ultimate conclusions.

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