COSMIC X-RAY SOURCES

Introduction

The atmosphere of the Earth is opaque to most wavelengths of light in the infrared, in the ultraviolet and in the X-rays. Due to this fact observation of celestial objects in X-rays (in the range of energies from 0.5 to 20 keV) must be carried out outside the atmosphere at altitudes greater than 100 kilometers, namely from space. The development of X-ray astronomy had therefore to await the development of rocket and satellite borne instrumentation.

The first observations of solar X-rays were carried out in 1948 from captured German V-2 rockets by the group at the Naval Research Laboratories (NRL) led by Herbert Friedman. The first observation of extra- solar x-ray sources was obtained in 1962 from an Aerobee rocket by the group at American Science and Engineering (AS&E) led by Riccardo Giacconi.

In the fifty years since then x-ray astronomy has grown to be an important branch of astronomy on par with optical, infrared and radio. The sensitivity of X-ray observations has increased in this period by more than 10 billion times, an improvement equal to that achieved in optical astronomy from the naked eye to the 10 meter telescopes, which occurred over 400 years.

This improvement in sensitivity of the instrumentation has allowed the study of X-ray emission from all types of celestial objects from planetary magnetospheres to stars, to the most distant quasars in the universe. As described in what follows X-ray observations have permitted the discovery of previously unknown celestial objects and states of matter.

The importance of these studies is due to the prevalence of high energy phenomena in the formation and dynamic evolution of stars and galaxies. High energy phenomena are events such as explosive processes where particles are accelerated to relativistic energies, or processes resulting in the heating of plasmas to extremely high temperatures (100 million degrees).

All of these phenomena are copious emitters of X-rays which are the lowest energy photons more energetic than UV (and therefore the most numerous) that can reach us from cosmological distances. Furthermore X-rays (as opposed to gamma rays) can be focused with grazing incidence telescopes and it is the development of these telescopes which has permitted the rapid improvement in sensitivity noted above.

In the last decades X-ray observations have become a necessary and fundamental tool to study the Universe.

Instrumentation

Observations in X-ray astronomy consist normally in the detection of individual photons. In the 50s and 60s, thin window Geiger or proportional counters were used. The Geiger counters detected each photon absorbed in their gaseous volume, but gave no information as to its energy; in the proportional counters the electrical signal produced by each photon was proportional to its energy. Geiger counters and proportional counters were used in the discovery flights of NRL and AS&E, in the first X-ray observatory “UHURU” in 1970, and in the “High Energy Astronomical Observatory-A” in 1977. The sensitivity of these detectors was limited by the background and it could therefore only increase with the square root of the area. The 100 square foot detector on HEAO-A was only 7 times more sensitive than the 2 square foot detector of UHURU.

Figure 1: NASA's Chandra X-ray Observatory was deployed by the Space Shuttle Columbia on July 23, 1999.

The breakthrough in X-ray astronomy occurred with the development of X-ray grazing incidence telescopes by the AS&E group in Cambridge, Massachusetts. In particular, Leon Van Speybroeck and Giuseppe Vaiana of that group succeeded in designing and building X-ray telescopes of increasingly high angular resolution (see Giacconi et al. 1969). In 1968 the first high resolution picture of the Sun (5 arc seconds) was obtained in a rocket flight by the AS&E group. In 1973 the same group achieved equal resolution in a set of photographs extending over a full solar rotation with a 30 cm diameter telescope on SKYLAB, the first manned Space Station.

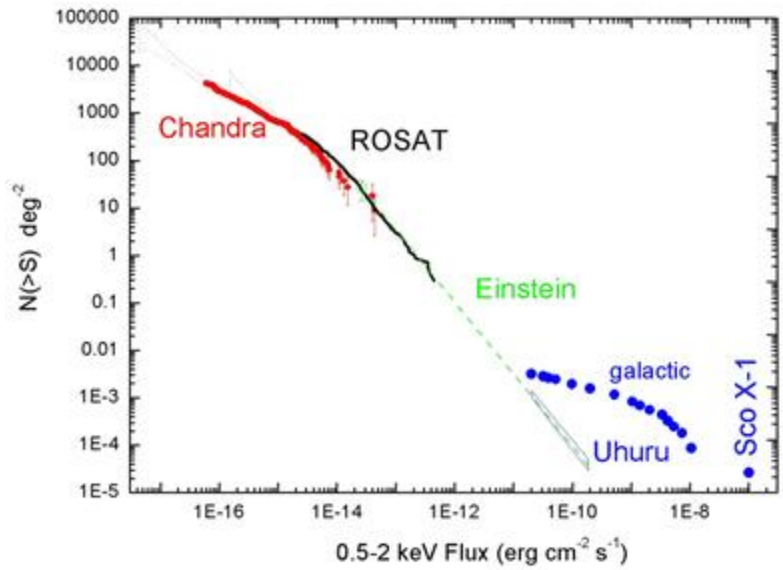

Figure 2: Progress in sensitivity in 40 years of X-ray astronomy. Number of sources per square degree, N(>S), brighter than a given flux, S, for the 0.5–2 keV band. Courtesy of G.Hasinger.

Imaging X-ray telescopes of increasing size and resolution were flown for extra-solar X-ray astronomy on the “EINSTEIN” observatory by Giacconi’s CFA group in 1978 [7] (60 cm, 4 arc seconds); on ROSAT by J.Trümper at the Max Plank Institute in 1990 [8] (80 cm, 5 arc seconds); and on CHANDRA in 1999 (120 cm, 0.5 arc second in the center of a 16x16 arc minutes field, Figure 1).

Other grazing incidence collectors have used approximations to the ideal conics optics to obtain varying degrees of concentration of the X-ray flux, angular resolution and fields of view. XMM-Newton is a Wolter optic with a modest resolution (~10 arcsec).

The detectors which are used in the focal plane of these telescopes have been imaging proportional counters, photoelectric high resolution imaging channeltron devices, and in the last few years charge coupled devices similar to those used in the optical domain. The combination of these technical advances has resulted in a 10 order of magnitude increase in sensitivity from 3×10^{-7}erg/cm^2/s , the flux detected from Sco X-1 (the first source discovered), to the flux of 3×10^{-17}erg/cm^2/s detected with CHANDRA in the deepest surveys (Figure 2).

Solar and stellar X-ray emission

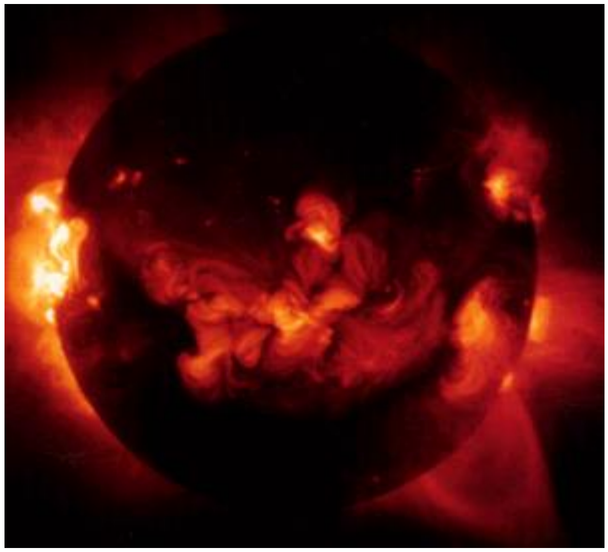

Figure 3: Image of the Sun at soft X-ray wavelengths (0.25-4 keV) recorded by the Yohkoh satellite.

Solar emission from the sun occurs because convective currents bring strong magnetic fields to the surface and thus can heat the coronal gases to temperatures of 10 million degrees. The magnetic field contains and accelerates the plasmas as shown by the X-ray pictures (Figure 3). Many other normal stars have convective zones in their interior and produce X-rays by similar mechanisms. Recent CHANDRA observations of O supergiant stars have been interpreted as the result of the interaction of stellar winds in binaries as well as magnetically channeled wind shocks. The interaction of stellar winds with the interstellar medium may be responsible for the diffuse emission seen in young star clusters.

Supernova remnants and neutron stars

Neutron stars are the remnants of massive stars which have burned their elements into iron. The core of the star no longer produces enough energy to withstand gravitational collapse. The core collapses until at a density of about 10^{15}g/cm^{3} all matter is turned into a neutron gas which can maintain a stable configuration.

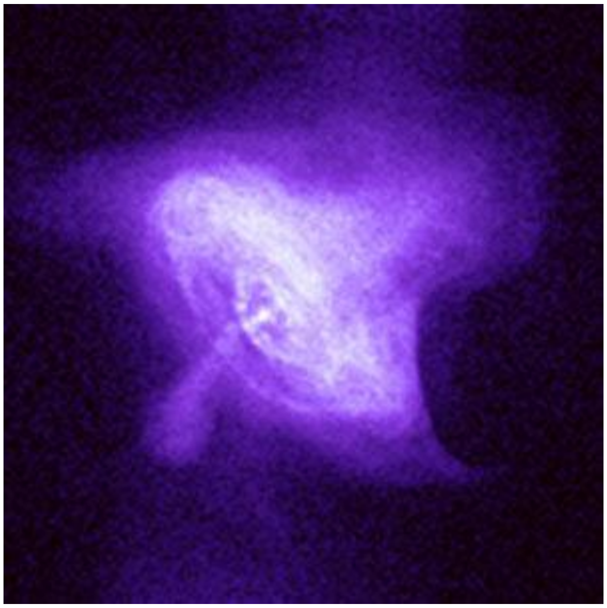

Figure 4: *Chandra* image of the Crab Nebula showing the central pulsar, the remnant of a supernova seen in 1054 AD, and a complex structure created by high-energy particles spiraling around rings and along jets in perpendicular direction (Credit: NASA/CXC/SAO/J.Hester et al.[1]).

The rotational kinetic energy of the star prior to collapse is transferred to the neutron star, which rotates very rapidly at its birth. The magnetic field of the star prior to collapse is also transferred to the neutron star and is greatly intensified. The interaction of the rapidly rotating magnetic field with particles can accelerate these particles to relativistic energies of 10^{14} eV. These particles produce the radio, optical and X-ray emissions from the pulsar through synchrotron radiation (Figure 4). The energy source is the rotational energy stored in the neutron star which slowly dissipates resulting in a slowdown of the rotation. Neutron stars were discovered in 1967 by Hewish and Bell though their rapid periodic pulsations in radio waves.

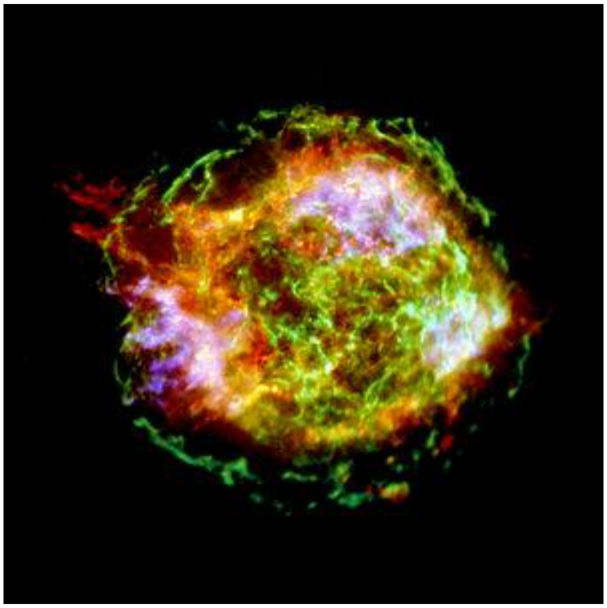

Figure 5: One-million second *Chandra* image of the supernova remnant Cassiopeia A. The red, green and blue colors correspond to X-rays of increasing energy (Credit: NASA/CXC/GSFC/U.Hwang et al.).

The energy dissipated in the stellar collapse drives out the outer layers of the star in a supernova explosion. Such events were known to Tycho and Kepler 400 years ago. The outer layers of the star expand outward at speeds of thousands of kilometers per second, plow into the interstellar medium and create an expanding shell of hot gas, at temperatures of million of degrees, which emits strongly in the X-rays (Figure 5, U.Hwang et al.). X-ray spectra of these shells allow us to determine their metal composition. They expand in the interstellar medium and mix with it to provide the enriched material required to form systems of stars and planets similar to our own solar system, capable therefore to sustain life.

Binary X-ray sources

The discovery of X-ray binaries was crucial in clarifying the nature of most of the high- luminosity galactic sources. X-ray binaries are systems composed of a normal star and a collapsed companion, either a neutron star or a black hole. Cen X-3 and Her X-1 were the first systems containing a neutron star that were fully understood in terms of their source of energy and emission processes (Schreier et al. 1972, Tananbaum et al. 1972). Cyg X-1 was the first system that was shown to contain a black hole of a few solar masses.

Cen X-3 and Her X-1 exhibit periodic pulsations with 4.8 and 1.2 second periods. They show occultations and Doppler shifts in the rapid pulsations in phase with the occultations. The conclusion is that they are binary systems with 2.1 and 1.7 days period. The compact object is a neutron star.

The gas from the normal companion falls in the deep potential well of the compact object and it acquires energy of order of 100 MeV per nucleon. This energy is transformed in heating of the gas as it spirals in the accretion disk and as it reaches the surface of the neutron star. Due to the high temperature the gas is a fully ionized plasma which is guided to the magnetic poles of the star. As the star rotates this produces the characteristic periodic pulsations (Figure 6). A very small mass loss from the companion is sufficient to power the X-ray luminosity of 10^{38} erg/sec some 10,000 times the total luminosity of the Sun. The accretion of gas onto the neutron star imparts angular momentum to the star which is gaining rather than loosing rotational kinetic energy, a process completely opposite to what happens in the emission from isolated pulsars. The frequency of the rapid pulsations therefore is increasing rather than decreasing with time.

From these discoveries we learned that if neutron stars are produced in supernova explosions these explosions do not disrupt the binary system in which they occur; also that accretion on compact objects provides a very efficient source of energy, some 50 times more effective than nuclear burning.

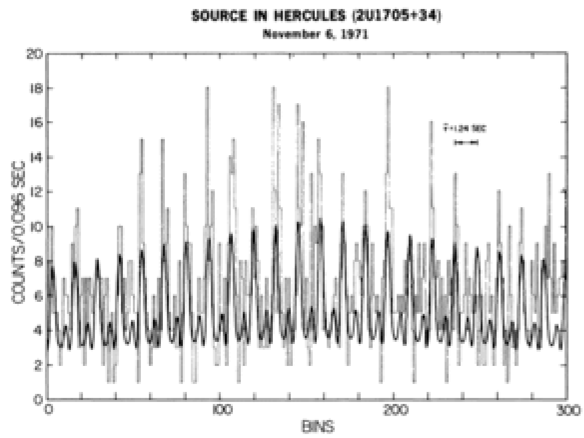

Figure 6: X-ray pulsations of Her X-1 discovered with*UHURU* [2].

Figure 7: Artist conception of the binary system Cyg X-1 (Illustration of L.Cohen).

In Cyg X-1 a high degree of variability in time scales as short as 1 millisecond was discovered. No long term periodicity was seen. The optical counterpart was found to be a 5.6 day spectroscopic binary (Webster and Murdin and Bolton). The companion star is a super giant of about 30 solar masses leading to a mass for the compact object of 6 solar masses, much in excess of the limit of 3 solar masses for neutron stars (derived by Rhoades and Ruffini). The rapid variability and its large scale sets a constraint of 3×10^7 cm on the diameter of the source. Thus the object is comparable in size to a neutron star but 2 or 3 times more massive. We know of no object with these characteristics except a black hole, a star predicted by Oppenheimer and Snyder in 1939. Zeldovich and Novikov had predicted their discovery through their X-ray emission in 1964 (Figure 7). (See Review in "Accretion-Driven Stellar X-ray Sources")

The very high efficiency for energy production through gravitational infall provided the physical starting point to explain the high luminosity of Active Galactic Nuclei and quasi stellar objects as due to black holes with masses of 10^6 to 10^9 solar masses in their centers accreting matter from the galaxy in which they are imbedded.

X-ray emission from galaxies and active galactic nuclei

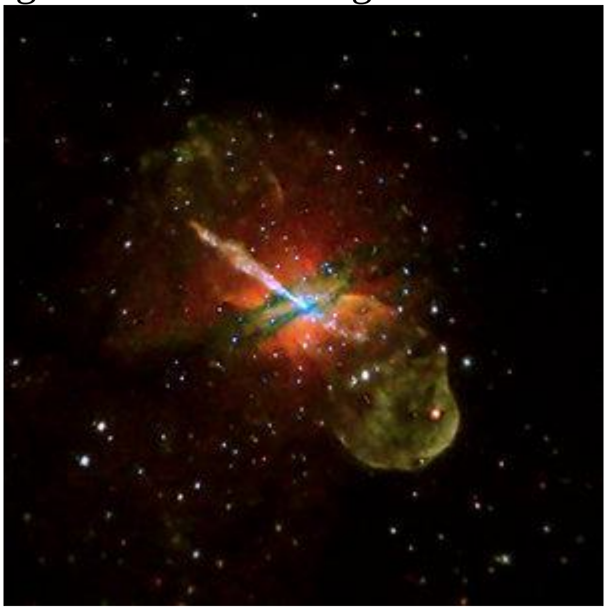

Figure 8: *Chandra* X-ray color image of the Centaurus A galaxy powered by a central super-massive black hole. (Credit: NASA/CXC/CfA/R.Kraft et al. [3]).

Normal galaxies emit X-rays due to the sum of the X-ray emission of main sequence stars, neutron stars, binary X-ray sources, supernova remnants and diffuse gas. The total X-ray emission is of order 10^{39} to 10^{42} erg/sec in the 0.5 to 5 keV range.

Most galaxies (including our own) have massive black holes in their centers. As these black holes grow by accretion from the surrounding galaxy their X-ray emission tends to dominate the total emission of the galaxy. Such objects are called active galaxies (AGNs) or QSOs and can reach luminosities of 10^{46} erg/sec. The X-ray emission is powered by gravitational infall of matter onto the massive black hole at the center from an accretion disk. Time variability on relatively short time scales (less than 1 year) is made possible by the relatively small dimensions of the central engine, and is frequently observed.

A frequent by product of the accretion process is the production of jets in the direction perpendicular to the plane of the accretion disk. High energy particles are accelerated to very great distances (Mpc) from the nucleus. The process of formation of these jets and the continued acceleration of the particles in them to make up for their radiative losses is not fully understood (Figure 8: deep *Chandra* observations of Cen A by Hardcastle et al. 2007).

Source : http://www.scholarpedia.org/article/Cosmic_X-ray_sources