Astronomy 1Bh *The New Astronomies* **Spring 2001**

UV & X-ray astronomy

Though we can't see much below 400 nm, the Earth's atmosphere is in fact fairly transparent down to 310 nm, so it is possible to operate ordinary photographic and photoelectric detectors in the 'near' UV. 'Real' UV, $\lambda < 310$ nm, is blocked by ozone (O_3) and other atmospheric constituents, and began to be studied only when high-altitude rockets (captured German V-2) became available after World War 2. Rockets could spend only a few minutes above the ozone layer (~ 25 km), and were eventually superseded by high-orbiting satellites that could survey the UV sky for months or years. Up to the present, these have measured the UV spectral distribution for single objects, one-by-one.

UV OBSERVATORIES IN SPACE A series of Orbiting Astronomical Observatories for UV astronomy culminated in the very successful OAO-C ('Copernicus') launched in 1972. The European TD-1 satellite (1972) carried UV photometers which contributed to an extensive all-sky UV catalogue compiled at Edinburgh and Liège. Various Shuttle-borne UV telescopes have operated. IUE, the International Ultraviolet Explorer, launched in 1978 and only closed in 1997, was arguably the most productive single observing facility of all time. It obtained high-resolution UV spectra ($\lambda = 115 - 320$ nm) of individual objects. IUE operated as a remote-controlled observatory in space, obeying the commands of ground-based astronomers (over 1500 individuals). (Astronomy Now, June 1992).

The Hubble Space Telescope is the first spacecraft to include UV imaging among its functions. This is a valuable contribution, in addition to the optical imaging quality, now restored to its proper capabilities.

ASTROPHYSICS IN THE UV

UV astronomy chiefly concerns hot objects ($> 10,000$ K). The photons involved have high energies, and so do serious violence to any atom or molecule that intercepts them. In the spectra of gases (stellar or interstellar) the strongest lines are the **resonance lines** involving the ground state. These involve the biggest energy transitions and are thus frequently in the UV.

UV radiation causes **photoionization**, because the photons involved often have energies above what is required to ionize atoms, removing one or more orbital electrons. For example, interstellar hydrogen gas sits in the ground state where it can absorb the Lyman lines and a continuous range of wavelengths beyond the Lyman limit ($n = 1 \rightarrow \infty$) at 91.2 nm. Thus interstellar space is expected to be rather opaque below 91.2 nm, and most UV spacecraft so far have worked in the range 100 – 300 nm. NASA's EUVE (Extreme Ultraviolet Explorer) was launched in 1992 [Sky & Telescope, May 1993 and December 1994]. Once the gas is ionized, the atoms can reform, emitting **recombination radiation**; again, these lines occur principally in the UV.

Although it has been mentioned that interstellar space is rather opaque at wavelengths < 100 nm, an experiment on the joint Apollo-Soyuz spacecraft in 1975 suggested that the interstellar hydrogen is patchy enough that we may be able to see sufficient stars to probe the distribution of hydrogen clouds in the solar neighbourhood of our Galaxy. The resonance lines of some other important species, e.g. He and H_2, lie in this Extreme UV or **EUV** region. EUV telescopes require grazing-incidence optics as for X-ray telescopes (see below). Satellites that have explored this EUV waveband include the Extreme Ultraviolet Explorer (EUVE) and the X-ray spacecraft ROSAT [Sky & Telescope, August 1995].

UV ASTRONOMY

(1) STARS The Sun has been intensively observed in the UV, especially from the Skylab space station; UV pictures show the highly disturbed hot (100,000 K) region between the chromosphere (the upper atmosphere) and the corona (the even hotter extended outer envelope). UV spectra of other stars yield data on their chromospheres, and on **mass-loss** ('stellar winds') both from hot young stars and from cool stars; also on very hot **white dwarfs** soon after their formation.

(2) INTERSTELLAR MEDIUM Continuous absorption by interstellar dust rises steadily throughout the visible spectrum as λ decreases – that's why interstellar absorption is greater in the blue than in the red, so that distant stars appear **reddened**. Absorption continues to rise steadily in the UV, but around 220 nm there is a very strong 'bump' of extra absorption. Its cause is uncertain, but probably involves carbon, perhaps in the form of polycyclic aromatic hydrocarbons (carbon-ring molecules containing $\sim$ 60 C-atoms – 'buckyballs' etc). The Lyα line due to H atoms in the interstellar gas is a strong absorption feature; the corresponding weak absorption due to the rare deuterium isotope ('heavy hydrogen') gives an estimate of **deuterium** abundance which tells us the early baryon:photon ratio and hence determines a value for Ω_0 (see Big Bang course).

(3) QUASARS UV studies are important for active galactic nuclei (AGNs) and QSOs in two ways. (i) The energy output peaks in the UV, in the so-called 'Big Blue Bump'. Many people have argued this is just the spectral form you expect for an accretion disc around a supermassive black hole. (ii) In visible-region spectra of distant QSOs we see a 'Lyα forest' of dozens of Lyα absorption lines; this is of course a UV absorption line, but has been red-shifted all the way into the visible. The multiple lines probably means that the light of the quasar has been absorbed by a series of small cold gas clouds between us and the quasar. Without the quasar as a background light, we would never have known such intergalactic clouds existed [see Sky & Telescope, September 1997].

X-RAY ASTRONOMY

Röntgen discovered X-rays in 1895; he got the first Nobel Prize in Physics for his work. X-rays go through people but (fortunately) not through the atmosphere. You need rockets or spacecraft to do X-ray astronomy. The first cosmic X-rays, from the Sun's corona, were detected from V-2 rockets in 1948.

As we have seen, the EUV gap 100 – 10 nm is little explored so far. Beyond that, X-rays are conventionally divided into:

Soft X-rays	0.1 – 1 keV	(8 – 0.8 nm)
Hard X-rays	1 – 100 keV	(0.8 – 0.008 nm)

X-RAY EMISSION X-ray photons are mainly generated by a mixture of the processes discussed earlier. **Thermal free-free radiation** from gas at $10^6 - 10^8$ K is one common emission mechanism. The other is, paradoxically, the same mechanism that generates the very low-energy radio emission: **nonthermal synchrotron radiation**. The reason for this is that the ultrarelativistic electrons that generate the synchrotron emission can span a huge range of energies, thus giving contributions in all wavebands. A third possibility is a hybrid of these two: **inverse Compton emission**. Here, a low-energy photon can be struck by an ultrarelativistic electron, and kicked up to higher energies, rather like a ball being struck by a bat.

X-RAY TELESCOPES X-rays go through most materials and can't be focused by ordinary telescope mirrors. Early X-ray telescopes used grids to define the field-of-view, but of course very poor definition was obtained in this way. **Grazing-incidence** X-ray telescopes were developed in the 1970s and were used for good imaging in the highly successful EINSTEIN space X-ray observatory.

X-RAY DETECTORS X-rays would simply go through ordinary photon detectors. Instead, the ionizing energy of X-rays is used in a proportional counter. A box filled with gas (e.g. argon, carbon dioxide) is penetrated by X-ray photons entering through a metal-foil window, and their energy is absorbed by the gas atoms, producing ionization with the liberation of free electrons. These knock out further electrons, and the electron cloud is collected on a wire anode, generating a pulse whose size is proportional to the energy of the X-ray photon. (Remember the energy of a photon is proportional to its frequency – so by knowing the energy of each detected photon, you automatically get crude spectroscopy). For hard X-rays of energy > 30 keV, crystal scintillators (e.g sodium iodide) are used: incident X-rays generate light flashes that can be recorded by an ordinary phototube.

In recent years, detectors have been developed which use semi-conductors to absorb the X-rays, rather than gases or crystals. These have better energy discrimination, and so give better X-ray spectra.

X-RAY OBSERVATORIES IN SPACE After the Sun's corona, the first celestial X-ray source (Scorpius X-1) was detected from a rocket in 1962. The first X-ray satellite UHURU (1970 – 73) mapped the whole sky and located 160 sources; these were mostly concentrated towards the plane of the Milky Way, i.e. they were probably ('local') galactic objects, but a few corresponded with the positions of extragalactic objects. Sky-mapping was continued by the British ARIEL V (1974) and the American HEAO-1 (1977). Gradually the objects emitting the X-rays were hunted down. This was long hard work as the early X-ray source positions were very crude. Nearly all the objects concerned turned out to be unusual or highly energetic objects.

The EINSTEIN X-ray space observatory (1978) was a major breakthrough: 1000 times more sensitive than its predecessors and with a 58cm grazing-incidence telescope giving almost optical resolution. This has two major effects: (i) because of the accurate positions, it was now easy to identify X-ray sources, and (ii) because of the huge increase in sensitivity, X-ray astronomers could now detect relatively ordinary objects, such as stellar coronae, as well as bizarre objects like X-ray binaries. The next big advance was the German/US/UK ROSAT (Röntgen-Satellit), launched June 1990. It had an 84-cm soft X-ray telescope (0.1-2keV) and also a 58-cm wide-field XUV camera (6 – 30 nm). ROSAT mapped $\sim 250,000$ X-ray sources (UHURU found 160).

The start of the 21st Century has seen two major new X-ray observatories in space, which are set to transform the field with data of optical-like quality. NASA's Chandra (1999+) will give arcsecond-scale imaging (as good as optical). The European XMM was also launched in 1999. This has 10 times poorer resolution than Chandra, but is much more sensitive, with about 5 times the collecting area (effectively 1000 cm^2; this may not sound much, but in order to get even this XMM has to be the size of a bus).

HIGHLIGHTS OF X-RAY ASTRONOMY

(1) STELLAR CORONAE. The 'corona' of the Sun is a hot tenuous outer envelope that used to be visible only during eclipses, but it is a strong **soft X-ray** source ($T = 10^6$ K). How can the outermost part of the Sun be hotter than the 'surface' or photosphere? As well as thermal energy and radiation, energy is carried through the Sun in bulk motions (convection) and in magnetic fields; somehow this energy is released when it reaches the corona. Because the corona is so thin, even a modest heating effect leads to a high temperature. X-ray images of the Solar Corona show it is not uniform – it has loops and holes which change with time, including huge solar flares on timescales of minutes. This is all somehow controlled by unstable magnetic field patterns. Now we know that a wide range of stellar types, both cool and hot, are found to have X-ray emission from 'coronal activity'.

(2) X-RAY BINARIES: GRAVITY POWER These are very close double stars in which the more massive star has evolved into a collapsed object (a neutron star or a black hole). The two stars are so close that material in the outer atmosphere of the normal companion star can be more strongly attracted to the collapsed star, and streams down towards it. (Probably spiralling downwards in a so-called accretion disc). The gravitational potential energy lost is turned into heat, producing X-rays. For a collapsed star, energy generated this way can be more efficient than even nuclear burning. One kg of Hydrogen fusing to Helium liberates 6.4×10^{14} J; the same amount of matter falling onto a black hole should liberate roughly 10^{16} J. How do we arrive at this number?

Imagine a small amount of matter Δm falling onto a large mass M with radius R. Then the amount of energy it gains is $\Delta E = GM\Delta m/R$. So for a given mass, the more compact you can make it, the more energy you get. But the smallest something can be is a black hole with $R = 2GM/c^2$. Substituting, we find M and G cancel, and $\Delta E = \Delta mc^2/2$ – half the rest mass energy. In fact, doing this calculation properly using relativity, the energy liberated is exactly the rest-mass energy: creating matter at the event horizon of a black hole costs no energy, and this is how black holes are able to emit **Hawking radiation**. In practice, a lot of the matter will disappear down the black hole before it has time to radiate, so the true energy gain is a factor of about 10 smaller, but still many times larger than nuclear burning.

We know the sources are **binaries** because we see X-ray eclipses, as the collapsed object periodically passes behind the much larger normal star. Sometimes, where the collapsed object is a neutron star, we also see rapid X-ray pulses, as the neutron star spins. But we can actually see the pulse frequency change due to the Doppler effect as the binary orbit proceeds. Given the orbital period and velocity, we can work out the mass of the collapsed object. This is most reliable way we have of measuring the masses of neutron stars [See Sky & Telescope, May 1996].

(3) SUPERNOVA REMNANTS (SNRs) Most SNRs are X-ray sources, and as in the radio region, there are two types. Some, like Cas A, are **thermal X-ray sources**: the blast wave heats the interstellar gas to millions of degrees, which then radiates by free-free emission. In others, the SNR radiates **synchrotron emission** from particles accelerated either by turbulence in the blast wave, or by the pulsar (collapsed stellar remnant) left behind. The classic example is the Crab Nebula in Taurus (remnant of nova AD 1054), one of the first X-ray sources discovered. The spinning pulsar has rotational kinetic energy, but is slowing down. Calculations show that the rate at which rotational energy is being lost exactly matches the synchrotron luminosity of the Crab – i.e. the pulsar in this case is the direct power source for the whole nebula.

(4) AGN and QUASARS: more GRAVITY POWER? We discussed AGN and quasars earlier, in the radio section. They are very strong X-ray sources, and also rapidly variable, indicating a small size. In fact, although quasars were discovered by their radio emission, it turns out that only some of them are radio sources – but all of them are strong X-ray sources and even stronger UV sources. Following the success of the 'black hole binary' explanation of Galactic X-ray sources, it has been suggested that likewise gravity power is the explanation here. However the black hole required would be a 'supermassive object' – to explain the most luminous quasars, we probably need 10^9 solar masses.

(5) CLUSTERS OF GALAXIES Another surprise of early X-ray astronomy is that the space between galaxies in clusters of galaxies is not empty, but filled with a diffuse hot gas ($T \simeq 10^7$ K) which is emitting X-rays. In some clusters the X-rays are concentrated around individual galaxies; in others the distribution is smoother. Once again the ultimate energy source is gravity – the gas got hot as it started to collapse during the history of the Universe. Such a large mass of gas takes a very long time to cool – longer than the age of the Universe, so it is still hot today. The temperature and luminosity of this hot gas will depend on the total gravitating mass of the cluster – including the stars in the galaxies, the gas itself, and any dark matter there may be. Mapping out the cluster X-ray emission can then give us clues about dark matter, and how it is distributed. (See for example Sky and Telescope March 1992).

(6) THE X-RAY BACKGROUND Right from the earliest rocket flights it was found that there was a faint but uniform X-ray glow from all over the sky, as well as the discrete sources. In soft X-rays, we have now learned that a lot of this comes from hot gas in the plane of the Milky Way, but in hard X-rays it seems to be isotropic, and so is presumably extragalactic. For many years there have ben two rival hypotheses: (i) it comes from a hot **intergalactic gas** pervading the whole Universe, and (ii) it is actually the blurring together of many many faint sources that we simply haven't resolved yet – for example, distant quasars.

In an interesting example of the multi-wavelength nature of modern astrophysics, measurements by COBE at mm wavelengths seem to have ruled out the hot gas idea. If it existed, it should have distorted the cosmic microwave background, making it not quite a perfect blackbody... The cause of the X-ray background has to be faint active galaxies [Sky & Telescope, November 1995].