Observation of cosmic X-ray sources with the Netherlands astronomical satellite (ANS)

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Introduction

The history of X-ray astronomy is short. It began on 12th June 1962 when a rocket was launched from the U.S.A. with the object of determining whether the Moon, which at that time was in the southern sky, emitted X-radiation. It was indeed observed that, whenever the detector in the axially rotating rocket was pointed towards the south, the X-ray flux showed an increase. Although the resolving power of the detector was poor, it could nevertheless be seen that the peak of the radiation did not coincide with the direction of the Moon, but to a direction about twenty degrees away from it (fig. 1). The source of this radiation appeared to be in the constellation of Scorpius; it was later called Sco X-1, the first X-ray source in the Scorpius constellation.

On the same occasion it was found that a diffuse background of X-radiation was present that could not have been caused by extraneous particles. Thus, two fundamental discoveries were made at the same time: the background radiation and an X-ray source.

In subsequent experiments carried out during the sixties with rockets and also with balloons, the number of known sources was steadily increased, and more exact information was also obtained about the diffuse background. Since the time in which observations can be made with a rocket is short, owing to the short flight duration, the threshold sensitivity was not particularly good in spite of the use of very large detectors, and varied between 1 and 0.1 photon/cm²s.

The launching off the coast of Kenya of the satellite UHURU (Swahili for 'freedom') on 12th December 1970 was an immense step forward. This satellite, which had a long and useful life, had detectors in its equatorial plane which repeatedly scanned the same strip of the sky.

These facilities made it possible to reduce the weakest observable photon flux to about $10^{-2}$ photon/cm²s, and also — and this proved to be very important — to observe a number of sources for periods ranging from days to weeks. This revealed the presence of sources that show very considerable periodic variations in strength. Some of these sources were subsequently identified as X-ray-optical binary stars, i.e. two stars that rotate around each other in Keplerian orbits, so that part of the X-radiation is periodically eclipsed as seen from the Earth. It looks as if the observation of one of these objects provided the first clear indications of the existence of a 'black hole' in the galactic system. The variation in intensity was also investigated in detail and resulted in speculations about the evolution of neutron stars. This is especially interesting when the neutron star forms part of a binary system. Furthermore, in some X-ray sources an irregular and fairly slow variation was discovered.

It is scarcely surprising that the fascinating results achieved in this new area of research within such a short time gave rise to several plans to launch X-ray satellites. A survey of all the X-ray satellites that have meanwhile been launched, and those in preparation or under consideration, will be found in Table 1.

The feasibility of carrying out observations on cosmic X-ray sources is limited by two effects. The first is the absorption of X-rays by the Earth's atmosphere (see fig. 2), which is why these observations have to be made with rockets or satellites. It is true that the hard X-radiation from outer space can also be measured


instrument should preferably be sent to greater altitudes. This is even more important in measuring the softer X-rays, which are in a spectral region that has scarcely been investigated as yet and which we hope to learn more about with the ANS experiment. Satellite observations are also essential to permit a sufficient number of photons to be collected and to enable the variability of various X-ray sources to be studied.

The other limitation is due to interstellar gas. This consists mainly of hydrogen, but it also contains carbon, nitrogen, oxygen, neon and other gases. The absorption caused by the interstellar gas is wavelength-dependent (fig. 3). Although the density of the hydrogen particles in interstellar space is only of the order of 1 particle per cubic centimetre, and that of the other substances is smaller still, the strong continuous Lyman absorption of hydrogen is in itself sufficient to limit interstellar visibility at a wavelength of 300 Å to a few light-years. It is only at wavelengths of about 10 Å or shorter that we can penetrate to the galactic centre. This means that all we can see in the as yet virtually unexplored region of long X-ray wavelengths are the nearby X-ray sources. The more remote sources will be seen in a kind of haze, like a lantern in the mist.

In the next section we shall first go into some current

<table>
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<th>Satellite</th>
<th>Instrument</th>
<th>Operating mode</th>
<th>Energy range</th>
<th>Launching</th>
<th>Status</th>
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<td>in prepn</td>
<td>NL</td>
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<td>0.2-1000 keV</td>
<td>1975</td>
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<tr>
<td>CORSA</td>
<td>propl counters</td>
<td>pointing</td>
<td>0.2-100 keV</td>
<td>1975</td>
<td>in prepn</td>
<td>Japan</td>
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<tr>
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<td>pointing</td>
<td>0.1-150 keV</td>
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<td>pointing</td>
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<td>1979</td>
<td>under considn</td>
<td>U.K., NL, W. Germany</td>
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<td>in prepn</td>
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<td>0.1-1.5 keV</td>
<td>1979</td>
<td>in prepn</td>
<td>U.S.A.</td>
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problems of X-ray astronomy a little more deeply and consider the contribution which the ANS experiments might make towards their solution \[4\]. We shall then discuss the construction and operation of our experimental onboard equipment for measuring soft X-radiation. In the final section we shall briefly describe the American equipment for measuring hard X-radiation \[4\].

**X-ray astronomy**

The enormous advance of X-ray astronomy in only ten years has demonstrated the capability of this branch of astronomy to provide important new information not only on the nature of various interesting astronomical objects but also on the structure and composition of interstellar matter, and perhaps even of intergalactic matter.

Quite a number of X-ray sources that have been discovered in the past ten years have totally unexpected characteristics. Some of these objects emit tens of thousands of times more energy in the X-ray region than in all the other parts of the electromagnetic spectrum taken together (optical, infrared, radio, etc.). The diffuse background of X-radiation extends over a very wide range of energies, from soft X-radiation with wavelengths of about 50 Å up to the gamma-ray range \[5\]. A better understanding of this diffuse X-radiation could make an important contribution towards the solution of problems concerned with the structure and evolution of the universe.

One of the first important contributions to the theory of stellar X-ray sources was the discovery that various sources are located in a binary system and are associated with very compact stars, in the first place with neutron stars but also perhaps with 'black holes'. As a result a number of fundamental quantities are now known, such as the masses and dimensions of the X-ray sources, and in some cases the distance of the system from the Earth. Neutron stars provide a unique field of research for high-energy physicists. The densities in neutron stars \((10^{14}-10^{15} \text{ g/cm}^3)\) are many orders of magnitude greater than could ever conceivably be reproduced under laboratory conditions. The gravitational fields are so strong \((g = 10^{13} \text{ cm/s}^2\) at the surface\) that Newton’s laws are no longer applicable, and consequently the relativistic theories of gravitation (including the general theory of relativity) can in principle be tested against the observations. This applies in particular to one of the most important theoretical predictions of relativistic theories of gravitation: the existence of the black holes we have just referred to. These are objects whose radius \(R\) is smaller than the gravitational radius (or Schwarzschild radius) \(R_g\). For a non-rotating black hole \(R_g = 2GM/c^2\), where \(M\) is the mass of the object, \(G\) is the constant of gravitation, and \(c\) is the velocity of light. If \(M\) is equal to 1 solar mass, then \(R_g\) is about 2 km.

A characteristic of black holes is that neither matter nor electromagnetic radiation can escape from the region enclosed within the radius of gravitation, hence the name. Such objects can therefore only be observed by virtue of their gravitational field.

The X-ray source Cyg X-1 could well have some connection with a black hole. The X-ray emission probably originates from the immediate vicinity of the black hole, where the potential energy of the matter falling into the hole is partly radiated at a temperature of \(10^7-10^8\) K. The difference between the potential energy thus released from a neutron star and that from a black hole is not great enough, however, for us to be able to distinguish between them with any certainty, but we shall return to this subject presently.

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\[4\] A general description of the ANS project has been given by W. Bloemendal and C. Kramer in Philips tech. Rev. 33, 177, 1973.
\[5\] Relatively hard radiation is usually characterized by the quantum energy \(E\), relatively soft radiation by the wavelength \(\lambda\). The Netherlands satellite operates in the transitional region \((E = 0.1-10\text{ keV})\), in which both measures are used somewhat indiscriminately. The relation between them is: \(E(\text{keV}) \times \lambda(\text{Å}) = 12.39\).

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The final section is taken from a text kindly placed at our disposal by Dr. H. Gursky, Smithsonian Astrophysical Observatory, Cambridge, Mass., U.S.A.
First of all we shall give a brief outline of the present situation in X-ray astronomy, as mainly determined by measurements in the energy range above 1 keV (wavelengths shorter than about 10 Å). In the next section we shall then look at the significance of the soft X-radiation (wavelengths longer than about 20 Å), the wavelength region with which the Utrecht X-ray experiment will largely be concerned.

**Nature, number and spatial distribution of the X-ray sources**

Some 160 X-ray sources are now known. They vary in relative intensity (the flux on Earth) from 100 photons/cm²s in the wavelength region of 1-10 Å (the brightest source Scorpius X-1) to 0.01 photon/cm²s (the detection limit of the UHURU instruments). The positions of these sources are not yet very accurately established. The margin of uncertainty is about 1 square minute of arc for the strongest source to a few square degrees for some of the weaker sources. This is a serious handicap in X-ray astronomy, since identification with optical or radio objects or both is therefore difficult, which makes it difficult to obtain a better understanding of the type of object and of its physical nature.

Their distribution in the sky (see fig. 4) differs from that of the stars. In the stellar distribution there is a marked concentration of faint stars towards the Milky Way (hence the name), whereas the X-ray sources show a concentration of brighter objects towards the plane of the Milky Way, with a more or less isotropic distribution of faint sources beyond it. This suggests a subdivision into **galactic and extragalactic sources**, a subdivision which is fully supported by those objects that can be optically identified. In addition, the almost complete absence of a stronger background radiation in the

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**Fig. 4.** Distribution over the sky of the 161 X-ray sources now known [6], in galactic coordinates. The galactic longitude is plotted horizontally, the latitude $b$ vertically. Some sources are concentrated near the plane of the Milky Way ($b = 0$). These strong X-ray sources evidently belong to our own galaxy. There are also a number of X-ray sources, mostly weak, scattered more or less homogeneously over the sky, which have their origin in objects outside our galaxy (other galaxies, radio systems, quasars, etc.).

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**Fig. 5.** The elliptic galactic system M87 is characterized by a stream of outflowing matter, which is the source of strong synchrotron radiation in the optical and radio bands. This source also emits X-radiation, but the resolution of instruments that have so far flown is too poor for determining the origin within this system.

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**Fig. 6.** The most powerful radio source in the Centaurus constellation, Cen A, the galactic system NGC 5128 has also been found to be a source of intense X-radiation. The figure shows lines of equal intensity in the radio band. The radio emission evidently originates from two regions that are very remote but are symmetrical with respect to the galaxy. The position of the X-ray source was determined by comparing observations obtained with a slit-shaped field of view. The X-ray source does not coincide with the radio source but with the galaxy itself. The inset shows a magnification of the central part of the figure, giving the bearings used; and a schematic diagram of the optical image of the system. Also visible in the photograph, even more magnified, is the optical image itself. The X-ray source may perhaps indicate the site of an enormous explosion, the radio source being the remnants.
galactic plane, which might be the result of the total radiation of a large number of sources that are spatially unresolved, indicates that we can in fact observe all the stronger X-ray sources in our own galaxy. The total number of strong X-ray sources in our galaxy is therefore surprisingly small, being no more than about 100.

Extragalactic X-ray sources

Various weak X-ray sources can be identified with extragalactic objects. One of the first extragalactic sources to be identified was the giant galactic system M87. This is the well known system (see fig. 5) from which a stream of matter escapes that forms the source of very strong synchrotron radiation in the optical and radio bands of the spectrum. The X-ray-emitting band extends in space over about 0.7° (this is a linear diameter of about 200 kpc \(^{[7]}\)) and it is possible that the X-radiation is generated in a hot rarefied intergalactic gas between a number of members of the Virgo cluster of galaxies, one of which is the M87 system. (The whole Virgo cluster comprises some 1000 member and covers a region of about 10° diameter in the sky.) Other clusters of galaxies have also been identified as X-ray sources.

The existence of an intergalactic gas is tremendously important for our knowledge of extragalactic systems in general, and in particular for our knowledge of the structure of the universe. A rarefied gas between all galactic systems with an average density of approximately \(10^{-5}\) atom/cm\(^3\), for example, would be sufficient to bring the average density in the universe to about \(10^{-29}\) g/cm\(^3\), whereas observations on optically emitting matter (stars etc.) indicate an average density of only about \(10^{-31}\) g/cm\(^3\). The average density is an important parameter in models of the universe. Thus, if it were greater than \(10^{-29}\) g/cm\(^3\), it would mean that our universe was a 'closed' universe, in which the expansion now observed would gradually decrease.

Apart from clusters of galaxies, individual systems have also been identified as X-ray sources, such as the radio source Cen A (see fig. 6), the quasar 3C273 and various systems referred to as Seyfert galaxies, characterized by an intense activity in their nuclei. Our knowledge of the conditions prevailing in such galactic systems is still rather limited, however. X-ray astronomy can do much to add to that knowledge.

Finally, there is a fairly large class of extragalactic X-ray sources that have not been identified, even though their position is well enough known to make an optical identification possible. Plots of the numbers of X-ray sources as a function of their relative intensity show that their distribution is consistent with the assumption that the sources are homogeneously distributed in space, which means that they must be extragalactic. Further study of the characteristics of these intrinsic X-ray systems, about which we know very little as yet, is certainly needed.

\[\text{Fig. 7. The Crab nebula, in the Taurus constellation, consists of the remnants of a star that exploded in the year 1054, a supernova. The nebula itself and the remnant of the exploded star, a neutron star, together constitute a source of intense X-radiation.}\]

\[\text{Fig. 8. The Veil nebulae in the Cygnus constellation. These are very old remnants of a supernova explosion that presumably took place 30,000 to 50,000 years ago. The temperatures in this nebula are of the order of a few million degrees Kelvin, and the nebula therefore emits only soft radiation in the X-ray band (wavelengths longer than about 10 Å) and is not detectable at shorter wavelengths. The UHURU satellite could not therefore observe this source, but it will be studied extensively with ANS.}\]

Galactic X-ray sources

One of the first X-ray sources discovered was the Crab nebula, the still expanding remnants of the explosion of a supernova seen in the year 1054 (fig. 7). There are other, older supernova remnants that show X-ray emission, one of them being the gaseous nebula in the Cygnus constellation (Veil nebula, fig. 8). The sources extend in space from a few minutes of arc (Crab nebula) to a few degrees (Cygnus nebula).

Supernova remnants are among the best-explained X-ray sources, partly because of the wealth of informa-


\[^{[7]}\text{A pc (parsec) is }2 \times 10^5\text{ astronomical units (A.U.); }1\text{ A.U. = }1.5 \times 10^8\text{ km.}\]
tion obtained from the analysis of the emission in the optical and radio wavelength bands. The radiation from the Crab nebula is probably synchrotron radiation originating from the interaction between high-energy electrons with a magnetic field. Situated in the middle of the Crab nebula is a pulsar, a rapidly pulsating radio source (period 33 ms) whose optical and X-radiation also pulsates in intensity with the same period. It is thought that the pulsar is a rapidly rotating neutron star left over after the supernova explosion. It is the rotational energy of the pulsar that is finally emitted by the nebula in the form of continuous radiation. The period of the pulsar therefore gradually increases. The emission mechanism of the pulsar itself has not yet been explained in detail.

Of the two kinds of objects leads to the assumption, mentioned in the introduction, that X-ray sources of this kind must be neutron stars or perhaps black holes.

The development of the theory of X-ray sources received unexpected encouragement when it was found that some of them were members of binary star systems; the X-ray source is regularly eclipsed by an ordinary star. From the rotation period of such a system (about two days), from the duration of the eclipse (about half a day) and especially from the observed change in the pulsar period shown by the Doppler shift due to the orbital motion (see fig. 11), valuable information can be derived about quantities such as the mass of the X-ray source, the mass of the companion star, their dimensions and the distance between them. If the companion star has also been optically identified, something can usually be said as well about the distance to the system. Seven such binary-star X-ray source systems are now known.

The only system among these seven that has at the same time been optically identified, shows eclipses and is also an X-ray pulsar, is Hercules X-1. This is therefore the system on which we have the most information. In addition to the pulsar period of 1.24 s and the orbital period of 1.7 days, Her X-1 exhibits an unexplained on-off period of about 35 days (fig. 12); the source is seen to be alternately ‘on’ for 11 days and ‘off’ for 24 days.

X-ray sources in binary stars

Many X-ray sources exhibit fluctuations on every time scale on which they have so far been measured, from milliseconds to months. Two sources, Centaurus X-3 and Hercules X-1, are X-ray pulsars; they pulsate periodically with periods of 1.24 s and 4.8 s respectively (see fig. 9). There are a number of other sources that fluctuate irregularly; Cygnus X-1 and Circinus X-1 do so even within a few tens of milliseconds (see fig. 10). The inference from this is that an X-ray source of this type must have an extremely small diameter. The size of a region that flares up in say 10 ms must be smaller than the maximum distance that can be covered in that time by the information of this disturbance, i.e. smaller than 3000 km. The fact that on the other hand the very regular pulsations of the X-ray pulsars can only be explained in terms of the rotation of heavy objects leads to the assumption, mentioned in the introduction, that X-ray sources of this kind must be neutron stars or perhaps black holes.

Fig. 9. The intensity of the emission from the X-ray sources Centaurus X-3 and Hercules X-1 fluctuates with periods of 4.8 s and 1.24 s respectively, hence the name X-ray pulsar. The pulsations are thought to be caused by matter falling inward on to the magnetic poles of a neutron star. (On neutron stars there is thus a kind of polar aurora, but of course very much more intense than those on Earth.) Because of the rotation of the neutron star these poles are obscured alternately as seen from Earth, which explains the pulsating nature of this X-ray source. The graph shows a measurement on Cen X-3, which extended over a time interval of about 100 seconds (1 scale division = 0.0965 s).[*]
Fig. 10. The observed intensity of the emission from the X-ray sources Cygnus X-1 and Circinus X-1 shows irregular fluctuations on a characteristic time scale, which may be very short (milliseconds). The radiation source here could be the immediate vicinity of a ‘black hole’, an even more compact object than a neutron star. One scale division on the time axis is 0.0965 s. [*]

Fig. 11. a) In addition to the pulsar period some X-ray sources also show a periodic fluctuation due to the regular disappearance and reappearance of the X-ray source behind a large, heavy ordinary star. This indicates that such neutron stars are apparently a component of a binary stellar system. b) Measurements on an X-ray source of this type. The lower curve shows the variation in X-ray intensity due to the regular disappearance of the source behind the other star. Associated with the movement of the pulsar around the centre of gravity of the system there are also regular changes in the pulsar period as a result of the Doppler effect (upper curve). The Doppler shift makes it possible to measure radial velocities very accurately, and to determine together with the orbital period the mass of the star and of the neutron star. [*]

The total energy radiated by such an X-ray source lies in a fairly narrow band and amounts to $10^{36}$ to $10^{38}$ erg/s, which is $10^3$ to $10^5$ times that from the Sun. This enormously high energy production by an object whose mass is of the order of one solar mass cannot be explained by nuclear fusion, as it can for ordinary stars. The energy production can however be understood in terms of the accretion of gas on compact objects, such as white dwarfs, neutron stars and black holes. In the case of a neutron star, for instance, with a mass equal to one solar mass and a radius of 10 km, some 10% of the rest-mass energy of the infalling gas can be released in this way, i.e. $10^{39}$ erg/g. An accretion rate of $10^{16}$ to $10^{18}$ g/s (which is about $10^{-10}$ to $10^{-8}$ of a solar mass per year) would then be amply sufficient to explain the total energy radiation. This relatively small flux of matter may well originate from the companion star, for example on account of the gradual expansion of this star during its evolution, so that it transfers matter to the X-ray source (fig. 13). This hypothesis has been quantified by detailed accretion models.

The maximum radiation intensity of the X-ray source is that at which the radiation pressure of the source prevents further accretion. This maximum intensity, called the Eddington limit, is calculated on the basis of the equality between the acceleration of gravity and that of the radiation pressure. Let $a$ be the effective cross-section for Thomson scatter, and $L$ the total intensity, then

$$\frac{aL}{4\pi r^2} = \frac{GM}{r^2}; \quad L_{\text{Edd}} = 10^{38}(M/M_0) \text{ erg/s},$$

where $M/M_0$ is the mass of the X-ray source in units...
Fig. 13. Mass transfer in a binary star system may be an important factor in the evolution of the system. At the time $t = 0$ the binary consisted of two stars whose masses are equal to 16 and 3 solar masses. The rotation period $P$ was 3.0 days. The dashed line is called the Lagrangian surface, being the equipotential surface in a revolving coordinate system that passes through the Lagrangian point. After 6.85 million years the more compact star, which evolves more rapidly, has become so large that it eventually fills a volume called the Roche lobe (the part within the Lagrangian surface). From then on, mass transfer can take place from the heavier to the lighter star. As a result the rotation period of the pair changes. When the overflow has reached the Langrangian point, the rotation period has then decreased to 1.5 days.

Measurements with ANS in the soft X-ray region

The Utrecht X-ray experiment with the ANS satellite is primarily concentrated on soft X-radiation (wavelengths between 20 and 70 Å). No satellite experiments have been carried out previously in this energy range, and our knowledge is therefore based on a few sounding-rocket experiments, in each of which the observation time was only a few minutes. These observations showed that the sky observed in the soft X-ray band is quite different from the sky observed at wavelengths between 1 and 10 Å. Some sources, including old supernova remnants like the Veil nebulae in Cygnus (fig. 8), radiate intensely in the soft X-ray region, whereas they are barely observable if at all between 1 and 10 Å, the energy range of the UHURU instruments. Emission of this nature may be expected from cosmic plasmas with temperatures of a few million degrees Kelvin.

Apart from the emission of these new, typically 'soft' X-ray sources, that of the 'hard' X-ray sources in the soft band is also important. In other words, the extension of the spectrum up to 70 Å would provide valuable new information. This is because the effective cross-section for the photo-ionization of hydrogen, helium and other gases by X-radiation increases strongly with increasing wavelength (see fig. 3). Measurements of this absorption effect make it possible to determine the column density of these elements between observer and source. Particularly if the source is time-dependent, as in binary systems, such measurements yield unique information.
information on the distribution of gas around the system.

In the soft X-ray range a 'diffuse' background is found which is considerably more intense than would be expected from an extrapolation of the diffuse background between 1 and 10 Å. It is not yet clear whether this arises from a large number of spatially indistinguishable galactic soft X-ray sources, or whether the radiation is really diffuse and originates from interstellar matter. A satellite experiment in the soft X-ray band is necessary as a first step towards solving the above problems and towards explaining the phenomena observed. The longer observation time would permit greater sensitivity, while at the same time a better survey of the whole sky would be obtained.

Summarizing, we may say that the first aim of the observations is to measure spectra and intensity variations as a function of time for sources whose position in the celestial sphere is fairly accurately known. The second aim is to scan certain regions of the sky systematically, especially in the long-wave band, a spectral region that has not been explored in this way before. For this purpose the Netherlands astronomical satellite will use the 'slow-scan mode' in which the scanning speed is 0.4°/min.

The Utrecht instrument for measuring soft X-rays; design and characteristics

The requirements to be met by the observations together with the fact that the instruments are carried by a satellite which can be accurately pointed but has a limited memory capacity, a special orbit, a limited permissible weight and a limited power supply, had a number of consequences for the design of the experimental system.

It is not possible to design a detector that is sensitive over the whole range from 6 keV to 150 eV. The Utrecht experimental package therefore consists of two detection units together with an electronics system for data processing. The soft X-ray detection unit consists of a parabolic mirror with a proportional counter with a small window area at its focus; for the harder radiation there is a proportional counter with a large window area, which has a mechanical collimator in front of it. The principal technical data are listed in Table II.

Before we go on to give a more or less detailed description of the instrument, we shall briefly discuss certain characteristics concerning the sensitivity, the required stability of certain parameters (in particular the gas amplification of the detectors), the minimizing of the background and the determination of the optimum field of view.

Since the sources we want to measure are in general extremely weak, it is necessary to make the radiation-collecting surface as large as possible. For the long-wave radiation this can be achieved with a fairly small detector by using a grazing-incidence optical system. When X-radiation is incident on a mirror at an angle smaller than the critical grazing angle, total reflection occurs. The critical grazing angle \( \theta_g \) is a function of the wavelength: \( \theta_g = C \sqrt{Z \mu / \lambda} \), where \( Z \) and \( \lambda \) are respectively the nuclear charge number, the atomic number and the density of the reflecting material; \( \lambda \) is the wavelength of the incident radiation and \( C \) is a constant. If the mirror has the form of a paraboloid, the entrance window of the detector can be small. This is important for minimizing the background radiation and increasing the life of the detector: the larger the window the more gas leaks away through it.

The optical system is not efficient for the detection of fairly hard X-radiation; since the critical angle is then very small, the paraboloid would have to be very long in proportion to its width and the geometric surface would still be relatively small. In this energy region a large-area detector is used in combination with a mechanical collimator. The proportional counters used for measuring X-radiation are fitted with extremely thin windows. For soft X-radiation (wavelength 44 Å and longer) polypropylene or a similar material is often used. A feature common to all such materials is that the carbon absorption edge results in a transmission characteristic like that illustrated in fig. 14. The value of the transmission at 44.7 Å and the extent of its exponential decrease at longer wavelengths depend on the thickness of the material.

Table II. Principal technical data for the Utrecht X-ray measuring instrument.

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<th>Parameter</th>
<th>Value</th>
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<td>Total weight</td>
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</tr>
<tr>
<td>Electrical power</td>
<td>3 watts</td>
</tr>
<tr>
<td>Measuring range</td>
<td>7 channels, 2-70 Å (1.5-2.3; 2.3-3.5; 3.5-4.9; 4.9-7.7; 7.7-20; 20-44; 44-70)</td>
</tr>
<tr>
<td>Angle between optical axes</td>
<td>3° (max.)</td>
</tr>
<tr>
<td>Field of view of parabolic detector configuration</td>
<td>circular-symmetric field, total half-width 40° or 50°</td>
</tr>
<tr>
<td>Field of view of large-area detector</td>
<td>along z-axis: total half-width 50° and 100°</td>
</tr>
<tr>
<td>Geometrical area of 44-70 Å detector</td>
<td>140 cm²</td>
</tr>
<tr>
<td>Geometrical area of 1.5-44 Å detector</td>
<td>150 cm²</td>
</tr>
</tbody>
</table>
The thin plastic windows are not completely gas-tight. The counter gas lost during the flight must of course be replenished, because the gas amplification of a proportional counter is a function of the density of the gas. The gas amplification must remain constant, otherwise the relation between the pulse height at the output of the detector and the energy of the incoming detected photon will gradually change.

Detectors with thin plastic windows have only been employed previously in rockets. The proportional counters used in rockets are of the flow-counter type; these have a controlled leakage, which is made much greater than the leakage through the window. This technique cannot easily be used for satellite experiments because of the large reserve of gas it would require.

The simplest method of controlling the gas amplification was assumed to be to provide the detector with an accurate and reliable pressure meter, and to use its indication for regulating the exact amount of gas to be injected. Since a pressure regulator of this type was not commercially available, we devised the following solution. Part of the detector system was designed in the form of a monitor counter, which is permanently irradiated by a radioactive source. The height of the output pulses from this counter is used as a signal to control the high-voltage supply. Since the gas amplification is also a function of the high voltage on the anode, we compensate the change in gas pressure by a change in the supply voltage. In this way a constant gas amplification can be obtained in a fairly wide pressure range. When so much gas has leaked away that the automatic control can no longer compensate for the gas loss, a command can be sent to the satellite for a quantity of gas to be supplied from the reservoir.

An incidental advantage of this high-voltage control is that the monitor will also react to very intense interfering radiation from the Van Allen belts. When the satellite passes through the radiation belts of the Earth, especially above the southern part of the Atlantic Ocean, where the density of the high-energy electrons is substantially greater than elsewhere at the same altitude, the high voltage will decrease. This will help to prolong the life of the detector. Of course, during this period no X-ray observations can be made.

A problem in the detection of X-radiation is that the detectors are also sensitive to high-energy particles. Much attention has therefore been devoted to minimizing the background radiation. The particle discrimination is based on the difference between the ionization tracks produced by high-energy particles and X-ray photons in a gas. A widely used method is therefore to surround the actual detector with a shield of anticoincidence counters.

The measurements of cosmic X-radiation previously carried out fall into two categories: on one hand, rocket measurements in the long-wavelength band, usually above 44 Å, and on the other hand rocket and satellite measurements in the short-wavelength band, using detectors that were almost invariably equipped with a beryllium window.
The transmission curve of a foil of beryllium 25 μm thick has already been shown in fig. 14. The curve shows directly why so few measurements have been carried out so far in the band between 12 Å and 44 Å (1 and 0.22 keV). However, this intermediate band is especially interesting because of the increase of interstellar absorption towards longer wavelengths (fig. 3). Also shown in fig. 14 is the transmission of a 1.7 μm titanium foil. As can be seen, the Ti shows extra transmission between 27 Å and about 35 Å. For this reason the large-area detector (surface area about 12 by 13 cm) is equipped with a Ti window.

Most of the previous experiments, mainly performed with rockets, were designed not only to measure the shape of the spectrum but also, and more particularly, the one actually obtained, and in addition the position of many of the sources to be observed is not exactly known. If the flat top of the angular-sensitivity curve of the instrument is higher than the sum of these uncertainties, the measured intensities can then safely be compared with one another, and we do not run the risk of spurious variations in the observed intensity.

The two detection units

For soft radiation

The detection unit for soft X-radiation consists of the paraboloid mentioned above, with a diaphragm-filter disc in the focus, and close behind it the detector with gas-filling system and reservoir; see fig. 16.

to determine the position of the source. What is then required is a transmission curve in which the sensitivity varies rapidly as a function of angle, e.g. a triangular sensitivity curve.

When the rocket or satellite rotates about its axis, the instrument scans the sky; in this way the position of the source can be accurately determined from the increase and decrease of the radiation intensity. In our case, where the position is assumed to be known and the main objective is to investigate the physical parameters of the sources, an angular-sensitivity curve with a flat top is required; ideally it should be rectangular in shape (fig. 15). For various reasons, e.g. if the optical axis of the instrument and that of the attitude-control system do not coincide, it may happen that the desired direction of observation does not entirely coincide with

The overriding requirement in the design of the paraboloid was of course to obtain the largest possible sensitive area within the limitations of volume and weight. For paraxial rays the angle of incidence is greater the closer they lie to the optical axis. Since reflection only occurs when this angle is smaller than the critical grazing angle, the central part of the paraboloid serves no purpose and can be omitted. The actual paraboloid used is suitable for 45 Å and longer wavelengths. The geometric surface area is about 140 cm². At the centre there is a shield that prevents radiation from reaching the detector directly. In front of the paraboloid is a 6-cm long vignetting tube, whose function is to block out radiation which would otherwise reach the detector.

Fig. 17. a) The parabolic reflector for radiation with a wavelength greater than 45 Å. S screen. T vignetting tube. The paths of three rays are shown. If the tube T were not there, ray 1 originating from the cosmic background, or from some source or other, would reach the detector without being reflected from the mirror. Ray 2, which would reach the mirror without being reflected, is blocked by the screen. Ray 3 belongs to a beam originating from the region of the sky within the desired field of view. The parabolic reflector directs this beam on to the detector. The left-hand part of the paraboloid does not contribute to the reflection. The angle of incidence here is greater than the critical angle.

b) Photograph of the paraboloid. The reflector was designed by the Space Research Laboratory at Utrecht and made by Philips Research Laboratories in Eindhoven. Typical of the dimensional accuracy is the size of the focus for paraxial radiation. The overall half-width of this focus is 0.18 mm. The focal length is 80 cm. The geometric surface is 140 cm². The weight is 3.3 kg.

along the shield, without being reflected from the mirror; see fig. 17. A diaphragm is situated at the position of the focus. Combination of the diaphragm, the shield and the tube produces an angular-sensitivity curve as shown in fig. 18. It should be noted here that a paraboloid is not an optically imaging instrument: paraxial rays are imaged at a point, while rays entering at a small angle form a ring in the focal plane. The paraboloid is therefore an X-ray collector.

The proportional counter, situated immediately behind the focus, has a polypropylene window 3.6 μm thick. A thin layer of aluminium (thickness about 200 Å) is deposited on the inside of the window to give a high-conductivity surface; deposited on the outside surface is a layer of graphite (thickness about 0.1 μm), whose function is to absorb ultraviolet radiation.

The detector is filled with 80% argon and 20% CO₂, and consists of three sections: two measuring sections and one anti-coincidence section. A radioactive source is permanently attached in front of the anti-coincidence section, so that it also serves as a sensor for the high-voltage control. All the sections are arranged in anti-coincidence with the others to discriminate against high-energy particles.

The basic diagram of the gas-filling system for the detector is shown in fig. 19. The pressure in the detector and the high voltage are measured during the flight;
every three minutes the measured data is stored in the memory on board the satellite. When the satellite arrives above the ground station this data is signalled back to Earth, and in addition these values are measured every 8 seconds during ground contact. If the pressure has dropped too much, the detector gas is replenished. This is done as follows: the valves $V_a$, $V_b$ and $V_c$ are normally closed, and the intermediate volume $IV$ is filled by opening valve $V_a$. The intermediate volume now contains a quantity of gas at pressure $P_I$ (75 atmospheres at the launch). One second later the valve $V_b$ is opened. If the pressure in the detector is not yet high enough, the procedure is repeated. As the gas reservoir empties the replenishment has to be more frequently repeated. This is not in itself a problem, since the replenishment and check on the effect can be performed very quickly. Valve $V_c$ serves for completely refilling the detector with fresh gas from time to time.

The diaphragm-filter disc can be set in four fixed positions in front of the detector. In this way it is possible to select two diaphragms for changing the aperture angle, a calibration position and a filter position. In the calibration position the light path to the detector is blocked. This is necessary because during certain periods in flight — after the launching and after a possible eclipse of the Sun by the Earth — a situation could arise in which the Sun was shining into the paraboloid. This would destroy the thin window. In the calibration position the measuring sections are irradiated by a $^{55}$Fe radioactive source, which emits almost monochromatic radiation of 2.1 $\AA$. In the fourth position a UV filter is interposed in the light path. In many rocket observations some difficulties have been encountered in the past from UV radiation. The use of a filter (MgF$_2$) that transmits ultraviolet rays but not X-rays enables the measurement to be carried out twice, with and without the filter, making it possible to distinguish between X-rays and ultraviolet rays.

For harder radiation

The detection unit for measuring the harder radiation, shown in fig. 20, consists of a large-area detector fitted with a Ti window. The gas mixture in the detector is Ne-CO$_2$.

The detector consists of four measuring sections, surrounded by four anti-coincidence counters (fig. 16). To cut down on the number of preamplifiers required, the anodes of section 1 and 3 and the anodes of sections 2 and 4 are directly interconnected. As in the case of the small detector for the long-wavelength range, one of the anti-coincidence sections is in the form of a

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**Fig. 19.** Principle of the gas-filling system. GB gas reservoir. PT pressure transducers. F particle filters. $V_a$, $V_b$, $V_c$ valves. IV intermediate volume. R restriction. Is insulator. Det detector. $V_1$, $V_2$ manual valves.

**Fig. 20.** The large-area array (see fig. 16). Col collimator. Det detector. El electronics. GB gas reservoir. Below the detector there is a gas-filling system similar to the one in fig. 19.

monitor counter, to act as a sensor for the high-voltage control. With metal foils the diffusion through the window is insignificant. It is very difficult, however, to obtain a rolled-metal foil free from pinholes so that here too a gas-filling system of the type just described is used. In the base of the detector there are two 13-μm thick aluminium windows. Two radioactive sources (²⁵⁰Fe and ⁹⁰Sr) are mounted on a shaft in front of these windows. The shaft is rotated about its axis by a small motor so as to bring the sources in line with the windows. For measurements in the normal mode, i.e. in anti-coincidence between the various sections, only the ⁵⁵Fe radiation is measured. The gas amplification and the resolution of the detector are directly determined from the position of the peak and its width. On the other hand, when the detector measures events that occur simultaneously in more than one section, only electrons are measured. The electrons from the ⁹⁰Sr source produce a broad pulse-height distribution, which enables the discriminator levels in the electronics to be determined.

Situated in front of the detector is a mechanical collimator, whose field of view is given in fig. 15. The collimator consists basically of two parts, one for sections 1 and 3 of the proportional counter, and one for sections 2 and 4. The collimator has a rectangular pattern of slits of two kinds, one measuring 1.4 x 2.5 mm and the other 1.4 x 4.85 mm; the bars in between are 0.25 mm thick. This collimator, which is 17 cm long and is composed of thin (1 mm) plates, was designed and made by the Institute of Applied Physics of the TNO-TH organization at Delft. To obtain the flat top in the angular-sensitivity curve, as previously discussed, there is a plate with a different pattern at the centre of the collimator. The two different fields of view make it possible to distinguish between the diffuse X-ray background and the intrinsic background of the detector itself.

Processing of the detector signals; methods of measurement

The pulse height at the output of the detectors is proportional to the energy of the detected photon. The energy spectrum is measured by counting the number of photons and selecting them by pulse height. In our case there are seven pulse-height channels. In deciding on the number of channels we took into account the limited memory capacity of the satellite, the low intensity of the sources and the limited resolution of the detectors. The resolution is inversely proportional to the square root of the energy. The seven channels are: 1.5-2.3 Å; 2.3-3.5 Å; 3.5-4.9 Å; 4.9-7.7 Å; 7.7-20 Å; 20-44 Å; 44-70 Å. The spectrum of an X-ray source will be determined by fitting a theoretical spectrum to the measured histogram, which will be done by choosing suitable values for the unknown parameters, such as the temperature of the X-ray source. Allowance should of course also be made for the wavelength-dependence of the instrument as a whole.

The instrument has eight memory registers. Seven of these registers, of 12 bits each, are used for storing the number of detected photons per integration period. The eighth register, of 16 bits, is used for storing the command word received from the onboard computer [9]. This determines the operating mode of the instrument, and it is also used for reporting back the result of the command (for example the position of the diaphragm-filter disc). At the end of each integration period, which may be either 1, 4 or 16 seconds, the onboard computer reads the contents of the 12-bit registers, reduces them to eight bits and stores the result in its memory. The reduction process consists in converting from binary to floating-point code (mantissa 4 bits, exponent 3 bits), or in shortening to 8 bits. The required duration of the measurement, the integration period and the conversion in the computer are determined beforehand by the experimenter for each object to be measured.

The attitude-control system has an offset facility for measuring the intensity of the background from time to time during the observation of an X-ray source [8]. The measurement using seven energy channels is referred to as the 'normal mode'. In this mode all pulses registered in the anti-coincidence counters are also stored from time to time.

For calibration the radioactive source is placed in front of the detector. Since the ⁵⁵Fe source emits near-monochromatic radiation, the resultant pulse-height distribution will be relatively narrow (half-width 18%). For this reason ten separate pulse height channels have been provided to measure this distribution. Since there are seven memory registers in the instrument, one detector calibration consists of two successive measurements in every five channels.

If there should prove to be intense X-ray sources whose spectra show fine structure — and there are indications that this will be the case — similar measurements could be carried out on X-ray sources. Measurements will then be carried out between 1.7 and 3.5 Å in ten channels. We call this the 'high-resolution mode'.

A third operating mode is the 'pulsar mode'. To measure the period of a pulsar we proceed as follows. The time of observation of each individual photon is measured to an accuracy of 1 ms (by counting the pulses from a 1024-Hz clock). Each of the seven registers is used for storing the detection time of one photon. In this way seven photons can be detected in each
integration period with a minimum of 1 second, but a
selection in terms of energy cannot be made at the
same time. A rough idea of the spectrum can be ob-
tained by finding out how many photons are counted
by one detector and how many by the other.

To determine the time of arrival to an accuracy of 1 ms we need
10 bits. Since the onboard computer is arranged to handle words
of 8 bits, it is useful to dispense with the two least-significant
bits to make the most efficient use of the memory. We then
obtain a resolution of 4 ms, which is sufficient for most cases.

A fourth operating mode, called the ‘high-time-
resolution mode’, was introduced in a late stage of the
design. When the results of the first X-ray satellite
(UHURU) were known, it turned out that the intensity
of many sources was extremely variable, even on time
scales smaller than one second. Measurements were
therefore needed with a resolving power of better than
one second.

With the seven registers we can make seven succes-
sive measurements; $\frac{1}{4}$ s in the first register, and so on.
In this way we increase the time resolution, though at
the expense of the information on photon energies. To
simplify the electronic circuits we use periods of $\frac{1}{4}$ s
instead of $\frac{1}{4}$ s, which means that we have a dead time of
$\frac{1}{4}$ s in every second. Just as in the pulsar mode, we can
again select either 2-44 Å radiation or 44-70 Å radia-
tion, or a combination of both. Using the 16-bit com-
mand word it is possible to select any required operat-
ing mode and any of the four positions of the dia-

\nofig. 21. The pulse-handling circuits of the Utrecht experimental system.

The American hard X-ray instrument

The hard X-ray instrument on board the ANS satel-
"life was built by American Science and Engineering
(AS & E) and the Massachusetts Institute of Technol-
gy (MIT), Cambridge, Massachusetts, U.S.A. It
consists of two instruments: a large-area detector and
a Bragg crystal spectrometer. The detector is designed
to measure X-ray emission from selected celestial
objects and regions in the energy range between 1 and
20 keV, using two closely collimated proportional
counters. The Bragg crystal spectrometer will measure
two Si emission lines between 1.8 and 2.0 keV, using
two Bragg crystals and collimated proportional coun-
ters. The instrument is shown in fig. 22.
**The large-area detector**

The large-area array consists of two collimated proportional counters of about 140 cm$^2$ each. This area is reduced, however, to an effective 40 cm$^2$ each by the losses due to the window structure (76% transmission), the fine collimator (50% transmission) and the coarse collimator (75% transmission). Each detector has a 10' x 3' field of view (half-width), but the optical axes (centre-lines) are offset by 5', giving an overall field of 15' x 3'. The effective total area is thus 60 cm$^2$. Differences between the counting rates of the two detectors can yield information on the direction in which...
the object is situated, thus providing an azimuthal reference. These differences are found by processing the individual data in the onboard computer. The separate counting rates will also serve as attitude-error signals in the X-ray pointing mode.

It is important that the proportional counters for the large-area detectors should maintain high efficiency over the whole range from 1 to 40 keV. The best filling gas for this purpose proved to be xenon, at a pressure of about 2 atmospheres with a small percentage of quench gas added (9.5% CO₂ + 0.5% He). The gas depth is 3.8 cm, which gives over 90% efficiency between 3 and 16 keV. Each counter has a beryllium window 25 μm thick. The data are analysed in fifteen pulse-height channels. The output of the proportional counters is subjected to pulse-shape discrimination to distinguish between pulses caused by X-rays and pulses due to gamma-ray induced events in the counter. The pulses caused by gamma radiation have a longer rise time than those caused by X-radiation. The aim is to reject about 90% of the gamma-induced pulses while accepting 90% of the X-rays in the 1 to 40 keV range.

The Bragg crystal spectrometer

After extensive investigations it was found that PET crystals — PET meaning C(CH₂OH)₄ — are suitable for measuring the line emission of Si, in the energy range between 1.8 and 2.0 keV. There are two crystals, each with an area of about 56 cm² and a projected area of about 40 cm². They are mounted so as to be sensitive to the spectral lines Si XIII and Si XIV with Bragg angles of 49°50' and 45°01' respectively. Independent proportional counters record the reflected X-rays from each crystal. The output pulses are recorded in eight pulse-height channels with the two Si emission-line energies corresponding to the centre energies of two of the eight channels. The relative positions of the two crystals are arranged so that when one of the two crystals is oriented at the critical angle for one of the lines, the other crystal is slightly off the critical angle of the second line. In this way the second crystal receives X-rays corresponding to the X-ray continuum, plus any fluorescence and scattered X-rays from the instrument collimators. Finally, since the large-area detector and one of the two Bragg crystals have the same orientation, it will be possible to measure the photon intensity of the X-ray continuum simultaneously in both detectors.

The Bragg detectors are designed to have a high efficiency near the Si lines. Argon gas at one atmosphere gives an efficiency of 66% for 2.0 keV radiation in a 3-cm thick counter. These counters also have beryllium windows approximately 25 μm thick. The transmission of these windows is about 70% at 2.0 keV and 80% at 2.5 keV. The net detection efficiency will in both cases be about 60%. The background is suppressed both by pulse-shape discrimination and by the use of anti-coincidence techniques. It should be possible to reduce the background counting rate to 0.1 counts per second in each detector.

Collimators, calibration and pulse-height analysis

The wire-grid collimators consist of six wire planes mounted in front of each of the large-area detectors. The field of view of each collimator is a slit, with a half-width of 10'. In addition the field of view is restricted by a tube-type collimator of 3° half-width, so that the net field of view is 10' × 3°. The tube-type collimator will be used to provide a 3° half-width field of view for the Bragg detector as well. The optical centre-lines of the large-area detector collimator and of the Bragg detector collimator are aligned parallel to within one minute of arc.

Radioactive calibration sources are mounted in a fixed position in front of each Bragg detector. The sources contain ¹⁹⁵Pt, which emits X-rays of around 10 keV. In the calibration mode the gain of the summing amplifier is reduced such that the 10-keV line corresponds to about 4 keV in the normal operating mode of the Bragg detectors.

As mentioned earlier, the pulse-height analyser processes the results of the detector measurements in fifteen energy channels, and those of the two Bragg detectors in eight energy channels. The detector-identification circuit indicates the source of the pulse and delivers control signals to the pulse-height analyser, to permit the data from either the 15-channel system or the 8-channel system to be transmitted and stored at the correct location. In all, the scientific data of this experiment are stored in 27 memory registers of 16 bits each, nominally fifteen for the large-area detector and four for each of two Bragg crystals. The read-out from the memory registers is controlled by the onboard computer.

Summary. The Netherlands astronomical satellite ANS carries on board two experimental packages for measuring the X-ray emission from cosmic sources: one is a Utrecht experiment and the other an American one. The American experimental system, built by American Science and Engineering (AS & E) and the Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, U.S.A., measures X-ray emission in the energy range between 1 and 20 keV. The Utrecht package consists of two instruments, one for the range from 2-44 Å and the other for the range from 44-70 Å. The 'soft' region has not previously been investigated with satellites. Owing to the fairly long pointing periods the ANS will be able to measure photon fluxes with a fair degree of accuracy, even including the emissions from fairly weak sources. A brief account is given of the present state of the art in X-ray astronomy, and of the knowledge acquired of X-ray sources so far measured, many of which — like the pulsars — are variable. The principal features of the instrument are described.
Heating quartz glass with a plasma torch

Extremely high temperatures can be produced with an r.f. argon-plasma torch, whose 'flame' is an ionized cloud of argon obtained by inductive heating. A working temperature of 10 000 °C is easily reached.

Torches of this type are coming into increasing use as emission sources for spectrochemical analysis [1], but they are also very suitable for rapidly heating an object to a high temperature. The photographs illustrate the use of a plasma torch for sealing the electrodes into a quartz-glass tube during the mechanical production of mercury-vapour lamps. The upper photograph shows the heating phase. The tube is near the middle of the picture. The argon gas required for the process is fed in through the pump stem of the quartz-glass tube. The r.f. coil moves downwards until it is around the lower end of the tube. The plasma torch is then ignited, and in about 3 seconds it heats the tube to 1800 °C; the coil then moves up again. Meanwhile, a cartridge in which the electrode is inserted (and perhaps an ignition electrode) is taken from a magazine transported by the slide at the upper left. (The slide can be seen below the hydraulic piston and to its left.) The cartridge moves to the heated end of the tube to place the electrode or electrodes in the correct position, and the tube is then sealed off with pincers (centre photograph). The pincers and cartridge are then moved aside, and the turntable and magazine shift up one position. As can be seen on the far right of both photographs, the tube is preheated with a gas flame immediately before the plasma heating. The bottom photograph shows a finished pinch, into which a discharge electrode and an ignition electrode have been sealed.

Heating with a plasma torch has various advantages over conventional methods. The heating is more homogeneous, giving a stronger pinch. The process is much quicker than with gas burners, and less energy is required; this helps to make conditions in the workshop more comfortable. The plasma torch is also very much quieter than the gas burner. Water is not produced in the heating process, as it is when hydrogen is burnt in conventional burners, so that the quartz glass is thus 'baked' clean, giving a better lamp.