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Cosmic X-ray Sources

[The 1972 Herstmonceux Conference was attended by 55 visitors. Dr. Alan Hunter opened the meeting and welcomed the visitors. Professor Cowling was Chairman of the first session and called upon Dr. Pounds to give the opening paper on "X-ray astronomy at Leicester".]

Dr. K. A. Pounds (Leicester). The most recent UHURU catalogue contains 116 X-ray sources with apparent brightness in the range ten times to one-thousandth of that of the Crab Nebula. A galactic coordinate plot shows that some two-thirds lie within 20° of the equator. These include all the brightest X-ray sources and are probably largely of galactic origin. It is notable, however, that the number of high-latitude sources has been considerably increased by the UHURU observations, and already the list of optically identified extra-galactic X-ray objects is impressive. These include three members of the Local Group (M31 and the two Magellanic Clouds), three powerful radio galaxies (Virgo A, Centaurus A, Cygnus A), two Seyfert galaxies (NGC 1275 and 4151) and the brightest known Q.S.O. (3C 273). The corresponding list of reliably identified galactic sources is no larger, comprising—in the author's view—six supernova remnants (Crab, Tycho, Cassiopeia A, Cygnus Loop, Vela X and Puppis A) and the stellar objects, apparently associated with highly compact stars, probably in binary systems (Scorpio X–1, Cygnus X–1, Cygnus X–2).

At Leicester, following our earlier rocket surveys from the southern hemisphere, we are concentrating on the detailed observation of individual sources, and I wish to mention briefly three recent experiments of this type. The exponential shape of the Scorpio X–1 spectrum has long been taken as indicative of a thermal X-ray mechanism, and an approximate source temperature of 50 million degrees may be derived. Ionization balance calculations show that strong line emission from *Fe* XXV and XXVI should be evident at these temperatures and a Bragg crystal spectrometer was flown early in 1971 on a Skylark rocket to search for these lines, as a definitive test of the thermal nature of the source. An upper limit of 25 electron volts was placed on the equivalent width (in terms of the local continuum) of the *Fe* XXV resonance line at 6·65 keV, compared with a predicted strength of 400 eV. It seems that all is not yet lost for the thermal models, however. Recent infra-red and optical measurements have shown the continuum to be optically thick at these wavelengths, indicating a compact, high density source, having a radius of about 10^9 centimetres and an electron density of 10^{16} per c.c. The high probability of photon–electron collisions within such a compact source, increased by resonance line absorption, appears sufficient to reduce the unscattered, narrow line component below the limit of the Leicester measurement. It is interesting to note that an extra factor of 2 or 3 in sensitivity could be crucial, since the absence of obvious distortion in the shape of the X-ray continuum of Scorpio X–1 places an upper limit on the scattering "optical depth" close to the value required by the absence of emission lines.

A second Skylark experiment, last September, was aimed at identifying the intense galactic source GX3+1 by the method of lunar occultation. With the aid of accurate predictions from Mr. Morrison of R.G.O. a Skylark rocket was launched at precisely the right moment (to a few seconds) and the occultation observed. As a result, the position of the source was placed along a short arc, some 2 arc minutes in length and 0·5 arc seconds in width, a precision exceeding that of any previous measurement and sufficient to pin-point a sixteenth-magnitude optical counterpart. A second occultation experiment by the M.S.S.L. group in October supported this suggested identification and reduced the larger dimension of the source error box to about 20 arc seconds.

The first reliably identified extragalactic object was M87 (or Virgo A) and the first spectral data were obtained by the Leicester group in 1968 and 1970. Evidence for variability was found and this has been made more intriguing by a recent UHURU report, with which I was concerned, showing the overall M87 source to be extended by about one degree. Very possibly this is a core–halo X-ray source, analogous to the radio counterpart. New, high-resolution X-ray observations will be of great interest.

Finally I would like to mention some recent analysis of the diffuse X-ray background spectrum from a rocket flight of November 1970. This has shown no significant mono-energetic feature at 6–7 keV, in disagreement with a previous N.R.L. report. The presence of a narrow feature in the background spectrum would, of course, be incompatible with the favoured universal origin of this radiation. Particularly careful account of all possible corrections to the observed continuum slope has also been made, yielding a photon power-law spectrum in the 1–10 keV range of dN/dE of approximately $E^{-1.6}$. We believe that this short stretch of well-determined background is sufficient to rule out the suggestion of a common power-law index (of about 2·2) from 1 keV to 1 MeV and also to confirm that a "bend" if not a "break" in the spectral index must occur somewhere between 20 and 200 keV.

Dr. C. D. Mackay. Is the M87 source centred on the galaxy? I seem to remember seeing in a recent paper that the source lay between M87 and M84.

Dr. Pounds. Newer data show an extended source centred within 2 arc minutes of M87. M84 is not seen as an X-ray source down to about 10 per cent of the M87 intensity.

Dr. F. Pacini. As the companion moves to the other side of Centaurus X–3 is there any spectral change?

Dr. Pounds. Because the occultation occurs gradually, over half an hour or so, as the X-ray source moves behind the extended atmosphere of the star, spectral changes should be evident, even in the restricted energy band of UHURU (2–20 keV). To my knowledge, this effect has not yet been looked for in the data.

Professor Cowling. Now I ask Dr. Miley to give his talk on "Radio observations of X-ray sources".

Dr. G. K. Miley (Leiden). I shall report observations of galactic and extragalactic X-ray sources carried out using the Westerbork Synthesis radio telescope at 1415 megahertz. At this frequency total intensity and polarization maps can be obtained with a resolution of about 22 seconds of arc. The noise after one twelve-hour observation corresponds to about 0·0013 flux units at the field centre, while 0·3 degrees away the sensitivity falls by a factor of 2.

First I will refer to the galactic sources. This programme, carried out with L. Braes, has two aims—the detection of new radio counterparts of X-ray sources and the study of the properties of known ones. The Westerbork telescope can pinpoint radio positions with an accuracy of about a second of arc, and therefore once a radio counterpart has been detected the search for an optical identification is narrowed to a very small area indeed.

During the last year we have monitored twelve of the strongest accessible X-ray sources whose X-ray positions are known to better than a few minutes of arc. In five cases we have detected faint radio sources in or near the X-ray error box, but only for three of them do we claim that the radio and X-ray sources are definitely associated. These three (Scorpio X–1, Cygnus X–1, and GX17+2) are all highly variable. For the other two sources (Cygnus X–2 and GX5–1) no variations have yet been observed, so we cannot rule out the possibility of chance coincidences.

Scorpio X–1 has a triple structure with the central component coinciding with the X-ray star. This central component is non-thermal and varies on a time-scale as short as twenty minutes. There is as yet no sign of any regularity in its behaviour or of any direct correlation with the optical and X-ray variations. The outer components are also non-thermal but their fluxes do not vary significantly. They are located symmetrically about 1·5 minutes of arc from the X-ray star and are probably relativistic plasmoids shot out in a previous outburst. We find no evidence for proper motion.

Like Scorpio X–1, the Cygnus X–1 radio source is also variable but in a very different way. This source was observed to appear within a three-week period about a year ago. We pointed out that it coincided with the ninth-magnitude BoIb star whose optical properties will be described later by Dr. Webster. After monitoring it for more than eight months we can say that apart from a slight decrease in flux after its initial appearance there is little evidence for subsequent radio variability and certainly no indication of periodicity. The absence of short-term variability makes Cygnus X–1 unique among the radio counterparts of galactic X-ray sources.

Now I want to discuss some measurements of radio sources located in rich clusters of galaxies. These were made in collaboration with C. Perola, P. C. van der Kruit and H. van der Laan. Ryle and Windram's work on the Perseus Cluster some years ago showed that NGC 1265 and IC 310 both had radio tails pointing roughly away from the strong compact radio galaxy NGC 1275. They proposed that a wind of relativistic particles from

NGC 1275 interacts with and "lights up" the other two galaxies. Subsequently Willson pointed out a similar pair in the Coma Cluster and Hill and Longair's identification of 3C 129 and 3C 129·1 brought a third case to light. Although the evidence for an interaction was not as convincing for Coma and 3C 129, Hill and Longair continued to adopt the interacting galaxies viewpoint in a modified and highly complicated form. The Westerbork observations of the Perseus Cluster have detected three more galaxies in the chain connecting NGC 1275 with IC 310. One of them has a radio tail which points not away from but nearly *towards* NGC 1275, and we feel that this is conclusive evidence against the interacting galaxies hypothesis.

We propose a much simpler explanation for the "head-tail" radio sources—namely that they are not causally related to any other galaxies. They are radio sources in their own right whose tails represent trajectories of galaxies ploughing through a dense intergalactic medium. Look at these radio photographs of NGC 1265 and 3C 129 and note the double structure not only of the heads but also of the tails! The polarization increases along the tail and in the case of 3C 129 reaches 60 per cent before it becomes noise-limited. Apart from their tails the structure of these sources resembles that of common double radio galaxies. According to current models of these more usual double sources, two relativistic plasmoids are ejected in opposite directions from the radio galaxy and are retarded by the ram pressure of the external medium. We believe that the "head-tail" sources can also be explained within the framework of these ram-pressure theories provided the galaxy moves at a high speed through the cluster's intergalactic medium. Evidence that this is the case comes from the radial-velocity dispersion of the Perseus Cluster which is the largest known.

Not only the head-tail sources but also several other complex 3C sources can be interpreted within this scheme. Whereas NGC 1265 and 3C 129 are narrow along their entire length, implying that the ejection velocity is more than the galaxy speed, 3C 465 and 3C 402 can be envisaged as systems where the ejection speed is less than the galaxy speed.

The fact that the optical galaxy always lies slightly in front of the radio heads implies that the dynamic ram pressure exceeds the internal pressure within the heads. Using this inequality we can derive a lower limit for the intergalactic gas density of between 2×10^{-28} and 2×10^{-27} grams per c.c., according to the relativistic proton contribution. These values, while high, are not unacceptable for the central regions of rich clusters and are compatible with the densities required for the extended X-ray sources.

Professor Cowling. Why do these galaxies show comet-like tails with a curve?

Dr. Miley. We are probably seeing a trajectory of the galaxy's orbit through the cluster. The simplest explanation would be that the curvature is due to gravitational bending.

Professor Cowling. Is there no rotational effect?

Dr. Miley. It's difficult to say because of projection effects. The only velocity information we have is the radial velocity. We need a larger number of candidates with tails to say more about the dynamics of the cluster.

Professor G. W. Hutchinson. What is the time scale for the ejection of the blobs in your picture of 3C 465?

Dr. Miley. The blobs are being continually emitted—the older blobs may be remnants of events a few times 10^7 years ago. 3C 129 has a longer tail than the others—if it has a velocity similar to that of NGC 1265, about 2000 kilometres per second, then its age would be about 10^8 years, which is compatible with the synchrotron cut-off.

Dr. Mackay. You made the point that NGC 1265 has a radial velocity 2000 kilometres per second greater than the mean for the Perseus cluster, but I believe the velocity of IC 310 is negligibly different from this mean.

Dr. Miley. The Perseus cluster has the largest velocity dispersion of any known cluster. We have only the observed radial velocity but it's reasonable to suppose that the transverse velocity could be high.

Dr. Mackay. The tail of 3C 129 is very long. I have the impression that the curvature at the end of the tail may be reversed.

Dr. Miley. There is some evidence that the galaxy is rotating. The tail may be almost helical.

Dr. S. J. Burnell. Going back to the galactic X-ray sources—your technique of aperture synthesis requires a long integration time. What are the most rapid variations you can follow?

Dr. Miley. This depends on the strength of the source. For Scorpio X-1 we cannot detect variations with a time scale below about 20 minutes.

Dr. G. M. Rowan-Robinson. We can deduce two consequences of your picture: first the velocities of ejection of the radio components are much less than the velocity of light, say one per cent of it. Secondly, the lifetimes of the relativistic electrons giving rise to the radio emission are rather long, practically as long as their lifetime in the black body radiation, against inverse Compton losses. This implies rather low magnetic fields, a microgauss or less, and therefore a big departure from equipartition. Would you agree with this?

Dr. Miley. The ejection speeds of the blobs would be quite low. Because we are speaking of a series of relatively low-energy events, however, one might expect lower ejection speeds than in the case of the usual double radio galaxy where the radio sources are formed in one energetic explosion. The equipartition energy is dependent on the volume and there is evidence that the tails are composed of several discrete blobs, which lowers the equipartition energies required.

Professor Cowling. The essence of it is that the ram-pressure is responsible for the confinement and it is not appreciably helped by the magnetic field.

Dr. Miley. The ram-pressure theories of Mills and Sturrock, of De Young and Axford and of Christiansen are very successful at explaining normal double radio galaxies.

Dr. Rowan-Robinson. The point about a big departure from equipartition is that the energy requirements are greatly increased. The energies involved in radio galaxies are already very large, assuming equipartition, so a big departure from equipartition does pose a problem.

Dr. Miley. The fields are still compatible with equipartition.

Dr. Pounds. The X-ray source in Perseus is now known to be extended by 40 or 50 arc minutes and is therefore large enough to cover the whole region of NGC 1275, NGC 1265 and IC 310. And another point, if we interpret the extended X-ray source due to inverse Compton radiation as radio electrons interacting with black-body photons, then we again require a magnetic field of less than a few times 10^{-7} gauss to be consistent with the radio emission.

Mr. N. C. Smart. What gravitational mass do you require to produce a curved tail for such a fast-moving object?

Dr. Miley. Assuming circular bending of the tail and a simple gravitational force we deduce a mass of a few times 10^{14} solar masses.

Professor Cowling. Dr. Murdin will now speak on the "Discovery of rapidly varying stars".

Dr. P. Murdin (Royal Greenwich Observatory). Cygnus X–1 was found to be variable on short time scales by the UHURU satellite as it scanned rapidly across the source, but Fourier analysis of long trains of data showed no peaks in the power spectrum. This raises the question of how to detect aperiodic fluctuations of a star. The ultimate limit of detection is governed by photon statistics, and an uncritical approach is to say that one may not detect fluctuations which are smaller than the statistical fluctuations. When the fluctuations are "rapid", in the sense that their time scale is comparable with the mean interval between observed photons, this could indicate that fluctuations of one magnitude or less are undetectable. Actually it is possible to do much better than this by scrutinizing the details of the distribution of the fluctuations. One has to count the number of photons, n, in intervals which are short compared with the time scale of the fluctuations. The distribution of n is Poissonian when there are no fluctuations; departures from the Poissonian law can provide information about the form of the light variation.

With Dr. H. B. Richer and Dr. H. M. van Horn at the University of Rochester, I observed the Crab Nebula pulsar, counting for ten minutes the number of photons in 4-millisecond intervals (the mean number of photons per interval was about 0·7). We found the r.m.s. modulation of the pulsar on the background of the Crab Nebula viewed through a twelve-second diaphragm to be $0{\cdot}204 \pm 0{\cdot}011$ magnitudes, and the ratio of the pulse-width to the period to be $0{\cdot}22 \pm 0{\cdot}09$. Both these data are consistent with the known facts about the pulsar light curve.

I applied the same techniques to all stars brighter than fifteenth visual magnitude in the original UHURU error box for Cygnus X–1. None showed positive evidence for fluctuations. In particular, the supergiant HD 226868, now known to be a spectroscopic binary and a radio source, was observed on 1971 May 28 and 29 with a sampling-time interval of 4 milliseconds for periods of 15 minutes. No fluctuations larger than 0·04 magnitudes r.m.s. value could be found over this frequency range of 4 cycles per hour to 250 hertz. If the X-ray source has the same optical luminosity as the Crab Nebula pulsar, it is 10 magnitudes fainter than the supergiant, and if modulated on/off would contribute an 0·0001 magnitude fluctuation to the combined light of star and source, so this result is not surprising.

Dr. D. W. Sciama. If you look at the fine details of the photon statistics do other points arise, receiver noise for example, or is it pure deviation from Poisson that tells you the intrinsic characteristics of the source?

Dr. Murdin. We have to allow for the dead time of the apparatus, which causes a skew to the photon distribution. This is easy to correct for if the source is faint.

Dr. J. V. Jelley. In the Crab pulsar, for example, is this method equivalent in signal-to-noise to using a multichannel analysis in direct mode?

Dr. Murdin. Not at all the same. The multichannel analysis picks out a tiny fraction of the power spectrum and looks for a signal enhancement in it, while this technique uses a very broad band width from the sampling time to the exposure time.

Dr. R. R. Hillier. Since photons are bosons do you expect them to satisfy Poisson statistics?

Dr. Murdin. I don't know whether you expect departures from Poisson statistics by the time the photons reach Earth when they may be milliseconds apart. We have found no evidence of such a departure for any star except in known variables.

Professor Cowling. One would expect any change in the statistics to be significant only in the source.

Professor D. Lynden-Bell. Do you see the seeing? If not, why not?

Dr. Murdin. There is a hint from over a hundred stars or so observed that there is a small residue of about one per cent fluctuation which may be attributable to atmospheric scintillation.

Professor Cowling. Thank you, Dr. Murdin. I shall now call on Dr. Webster to give her talk on "The observed properties of the Cygnus X–1 system".

Dr. B. L. Webster (Royal Greenwich Observatory). The strongest X-ray source in Cygnus, Cygnus X–1, has a two component X-ray spectrum. The soft X-rays have a steep spectrum and vary over time scales less than one second. The X-rays above about 10 keV have a harder spectrum and vary with time scales both of minutes and of times longer than the times of observations. Close to the X-ray position a very faint, variable radio source has been discovered by Dr. Miley and others which, if it is associated with the X-ray source, defines its position quite accurately as lying on the ninth-magnitude B0Ib star, HD 226868.

Dr. Murdin and I have taken a series of spectrograms of this star with the Isaac Newton Telescope, and find it to be a spectroscopic binary with a period of 5·6 days. The invisible companion star has a mass not less than two solar masses, which is too high to be a non-rotating white dwarf or neutron star. The long-time-scale variations in intensity of the hard X-rays can be plotted against phase, assuming a period near the optical one. For a period of 5·607 days these intensities define a rough curve with a minimum when the B star is at the point in its orbit away from the Earth. This minimum, if real, cannot, therefore, be regarded as the eclipse of a small X-ray emitting companion by the B supergiant.

We have also examined other bright stars in the fields of UHURU X-ray sources which are accessible at present. Of the four stars measured so far, none shows detectable radial-velocity variations.

Dr. Hillier. You questioned the reality of the X-ray variations in Cygnus X–1. The same variations are present in the hard X-ray data (that is greater than 20 keV) on the Crab and no one would say it is significant.

Dr. Webster. It seems important to look at one of these objects in the hard X-ray region for six days or so. It is unfortunate that the present satellites do not have the right energy range.

Dr. Pounds. As far as I know the UHURU observations in the lower energy range do not show the period of several days found for Cygnus X–1. It looks as though there are at least two components, which may behave differently, contributing to the X-ray spectrum.

[The second session was chaired by Dr. J. V. Jelley. He introduced Dr. F. Pacini who spoke on "Pulsar models of X-ray sources".]

Dr. F. Pacini (Frascati). Most likely, both pulsars and at least some types of X-ray sources are connected with the final stages of stellar evolution. A possible link between pulsars and X-ray sources is suggested also by the observational evidence. The pulsar NP 0532 is indeed a strong emitter of X-rays; on the other hand, the study of some X-ray sources such as Centaurus X–3 has revealed the presence of fast, regular periodicities. A genuine pulsar like NP 0532, however, is very different from a source like Centaurus X–3. The main difference is that genuine pulsars are highly non-thermal phenomena due to collimated motions of charges in the magnetosphere of a rotating neutron star. The X-ray emission is usually ascribed to the synchrotron process; if the pulses are emitted close to the speed of light distance, one can see that the intensity should be roughly proportional to $M^4 P^{-10}$ (M is the stellar magnetic moment, P the rotation period). Because of this, genuine pulsars can emit X-rays only if they are very fast or else they have a relatively long period but an exceptionally strong magnetic moment. The latter possibility could be realized also if some white dwarfs could give rise to the pulsar phenomenon. The same flux corresponds to a much higher value of M for white dwarfs than for neutron stars: this might partially compensate the disadvantage of longer periods.

In the case of sources like Centaurus X–3 the binary nature of the system and the suggested thermal character of the spectrum make it very likely that one is dealing with a system which has nothing to do with the standard pulsars. Rotating or vibrating white dwarfs, rotating neutron stars, black holes, all of them probably undergoing accretion, are all obvious candidates for investigation.

On the other hand, pulsars are important also because the rotation of compact stars can be the final energy source for some X-ray sources. It is well known that this is the case for the Crab Nebula, where the central pulsar is the continuous source of energetic particles. The details of the interaction between this pulsar and the Crab Nebula are only known in a first rough approximation. The existing model is largely based upon the idea that the pulsar emits low-frequency electromagnetic waves which then accelerate relativistic particles. Unfortunately up to now one has neglected the influence of the plasma itself on the low-frequency wave and all the complications arising from an index of refraction probably different from unity. Another effect to be considered is the presence of a nebular magnetic field different from the wave field. Until these effects (and probably others as well) are taken into account one cannot hope for a realistic description of the interaction of the pulsar with the Crab Nebula.

Finally, K. Davidson, E. Salpeter and I have suggested that some compact thermal X-ray sources like Scorpio X–1 might be pulsars embedded in a gaseous cocoon. In this case the energy would be originally transferred from the pulsar to the cocoon in a highly non-thermal form and then re-radiated thermally. If this is the case, it appears likely that the initial interaction of the relativistic particles with the cocoon will also lead to some γ-ray emission. If γ-rays are found from thermal X-ray sources, this would represent important evidence in favour of models of this sort.

Dr. Jelley. We have half an hour for discussion.

Mr. W. D. Evans. Do you expect radio emission in your model?

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Dr. Pacini. Yes. A few primary non-thermal particles will escape and give rise to an extended radio source.

Dr. Hillier. Does your model imply that the γ-rays will be pulsed?

Dr. Pacini. Some of them might! The higher energy γ-rays could be better off because of the lower effect of scattering.

Dr. Pounds. Any fast variations would tend to be washed out in the X-ray region.

Dr. Pacini. The photons trapped in the source would no longer have the collimated character. Depending on the density, it is clear to me that the pulses could be lost. Can I reverse the question? Has anyone looked for γ-rays from Scorpio X–1?

Dr. J. C. Jackson. Can you be specific about the spectrum of the γ-rays?

Dr. Pacini. No, but if they could be seen one would have some information about the energy spectrum of the primary particles.

Professor Lynden-Bell. I would like to ask about Rees's mechanism for rotating-dipole wave emission which you said was definitely inapplicable to the Crab pulsar on the basis of its polarization structure. However, this structure would be expected to be modified by reflections off the walls of the enclosure.

Dr. Pacini. I mean that if there are waves, the problem is more complicated than has been discussed up to now.

Dr. Webster. Would your model apply to other objects, for example Cygnus X–2?

Dr. Pacini. I applied this to Scorpio X–1 because most was known about this source. I would like to apply it to other compact sources as an alternative to accretion. The crucial test, whether the energy source is a thermal or non-thermal machine, might be from the γ-rays.

Dr. Jackson. Am I right in thinking you are mostly concerned in producing the thermal part of the spectrum?

Dr. Pacini. Yes, the other part can be made in several ways.

Professor Hutchinson. If γ-rays could be seen but X-rays thermalized, the envelope must be thick to X-rays but thin to γ-rays. This sets fairly close limits on its density and extent. How well are they known from other data?

Dr. Pacini. There are a few grams per c.c. and γ-rays would pass easily. It would be a mistake to look for γ-rays only from non-thermal sources.

Dr. Jelley. What are your views on photon–photon absorption? This may cause the loss of the γ-ray pulses.

Dr. Pacini. Perhaps so, but the photon density is relatively low.

Dr. Jelley. Any further questions? In that case we should thank Dr. Pacini again.

[The next session was chaired by Dr. J. S. Hey. The first paper, by Mr. J. Pringle, was entitled "Accretion models for variable X-ray sources".]

Mr. J. E. Pringle (Cambridge). I would like to say first that this talk stems from a joint piece of work by Dr. Martin Rees and myself.

The two powerful X-ray sources Cygnus X–1 and Centaurus X–3 are now known to form parts of binary systems, and moreover binary systems in which mass transfer seems to be taking place. We propose that the X-rays are produced by accretion from a "normal" component onto a compact component—either a neutron star or a black hole. To give the observed luminosities of the order of 10^{36} ergs per second we only need a mass flux of about 10^{-10} solar masses per year. Because of angular-momentum considerations we assume that accretion takes place by means of a circular disk around the compact object. In the disk, viscosity transports angular momentum outwards, allowing the gas to spiral slowly inwards. Most of the radiation comes from a region close to the compact object, and so as far as the X-ray emission is concerned we can ignore the effect of the companion star on the disk.

We can divide this theory of X-ray sources into models of two classes, Class I with a black hole as the compact object, and Class II with a neutron star. In Class I sources most of the radiation can come solely from the disk. The temperature of the gas in the disk varies with radius, in general increasing towards the centre. We obtain the overall emitted spectrum by integrating over the spectra emitted by the elemental rings that comprise the disk. In this way non-thermal spectra arise naturally and we suggest that Cygnus X–1 is of this type.

In Class II sources we can expect a large proportion of the radiation to be emitted thermally from the stellar surface. The disk could extend right down to the star, or it could become unstable before getting there. For example, if the mass flux is so large that the Eddington limit is violated, we would expect some kind of flaring process, with gas alternately being accreted and blown out. If the star has a substantial magnetic field (and is not rotating too fast) the accreted material will be funnelled down field lines on to the stellar surface. If the field is dipolar, the X-rays will come from hot spots at the magnetic poles. If the magnetic and rotation axes are not aligned, we would expect a large portion of the emitted radiation to be pulsed. This, we suggest, is the explanation of Centaurus X–3.

In summary, I would like to stress the variety of phenomena that can be explained by these models, despite their comparative simplicity.

Dr. Hey. Would anyone like to ask any questions?

Mr. A. M. Cruise. How steady would the accretion be? Could it account for the flickering X-ray output?

Mr. Pringle. It depends how steady the input flux is onto the star. There could be some sort of instability.

Professor Lynden-Bell. Do you have a basic preference for saying that the periods indicate the presence of a central object?

Mr. Pringle. Yes, that's what we hoped would turn out.

Dr. Pacini. In the case of black holes, can one anchor the field in the disk and get other cases?

Mr. Pringle. You would get no regular pulsation.

Dr. Hey. Thank you, Mr. Pringle. The next paper is by Dr. Jackson, on "A model of hard X-ray sources".

Dr. J. C. Jackson (Royal Greenwich Observatory). I shall talk about a mechanism for generating the variable hard X-rays from Cygnus X–1, which I hope will be of more general applicability to those galactic X-ray sources which turn out to be close binary systems. There is a sharp break in the spectrum of Cygnus X–1 at about 8 keV, above which the photon number spectral index is about 1·9 and the X-ray luminosity about 10^{37} ergs per second. By hard X-rays in this context I mean energies higher than this break point. The basic idea is that one component is a source of relativistic electrons and the other is an ordinary star, in this case a B supergiant. The electrons would collide with the photons from the ordinary star and produce high-energy photons by inverse Compton scattering. The attractive feature of the model is that it provides a natural explanation of the variability, and in particular the "anti-eclipse" phenomenon.

A relativistic electron with energy E and relativistic factor γ collides with photons of energy ϵ to give high energy photons with energy $\gamma^2\epsilon$ whose directions are concentrated in a narrow cone of angle $1/\gamma$ about the initial electron direction. This directional property is crucial to the model. An X-ray observer on Earth "sees" only those electrons which happen to be travelling towards him. Thus when the electron source is on the side of the ordinary star farthest from the observer, a significant fraction of the X-rays seen is produced by head-on collisions with low-energy photons, and when on the near side the relevant collisions are tail-on. As head-on collisions produce higher-energy photons than tail-on ones, this accounts for the variability, and in particular for the maximum apparent luminosity in the far-side position.

In the far-side position, a given observed X-ray energy E_x is generated by lower-energy electrons than in the near-side case. Thus the electron energy spectrum is important. Assuming a power law E^{-n} for this, and that the electrons are contained within a small region near their source, we find the observed photon flux $\propto E_x^{-\frac{1}{2}(n+1)} (1+\cos\theta)^{\frac{1}{2}(n+1)}$. Here θ is the angle between the line of sight and the line joining the two components, which varies as the electron source orbits its companion. Thus we have the standard inverse Compton spectrum modulated by the factor $(1+\cos\theta)^{\frac{1}{2}(n+1)}$, which is roughly what is observed.

For Cygnus X–1, I have assumed that the electrons are loosely contained, by a magnetic field of about 100 gauss, giving the emitting region a radius approximately equal to the component separation, of about thirty solar radii. We need 50 MeV electrons which interact with the 10 eV ultra-violet photons from the B star to give 100 keV X-ray photons. The energy densities are 100 ergs per c.c. (ultra-violet), and 400 ergs per c.c. (electrons and magnetic). The electrons would interact with the magnetic field to give infra-red radiation, between 100 and 300 microns, at flux densities of several times 10^{-23} watts per square metre per hertz. At longer wavelengths, self-absorption sets in; this may be what the radio astronomers are seeing at 10^{10} hertz. The nett inverse-Compton plus synchrotron luminosity is about 4×10^{37} ergs per second which is the required electron injection rate. The only objection to not containing the electrons is that they escape with all but a few per cent of their energy, pushing up the required injection rate to about 3×10^{38} ergs per second.

Dr. Hey. Thank you for your clear exposition. I'm sure there will be questions.

Dr. Pacini. Why don't you consider inverse Compton scattering of infra-red radiation?

Dr. Jackson. The first scattering is in the ultra-violet and would be difficult to see. The second would be in the γ-rays.

Dr. Sciama. You are saying that some infra-red photons go directly to X-rays. The numbers are such that these do not compete severely with those coming from scattering of ultra-violet photons.

Dr. Jackson. One has no evidence that the required electrons are there since there is a cut-off in the X-rays above 150 keV.

Dr. Hillier. Even if one doesn't accept the variation in the hard X-rays, we know they are there. If the photons and electrons come from the same star, you predict the hard X-rays anyway.

Dr. Jackson. Yes, but the new feature of this is an explanation of the variability, not just the X-rays.

Dr. Hillier. It is a common feature that there are thermal spectra at low energies and non-thermal at high energies.

Dr. Jackson. Yes, Scorpio X–1 has a break at 30 keV; it would be interesting to see if the hard tail shows anything like this variability.

Dr. Brand. Can your model fit the narrow minimum of the X-ray curve Dr. Webster has shown?

Dr. Jackson. I don't think it can and this worries me. I would like to see a full X-ray curve.

Dr. Hey. Any further questions? Well, thank you very much, Dr. Jackson.

[The next session was chaired by Professor Hutchinson, who called on Mr. L. V. Morrison to deliver his paper on "Lunar occultations of X-ray sources".]

Mr. L. V. Morrison (Royal Greenwich Observatory). If a record of the number of counts received per unit of time is obtained during the occultation of an X-ray source by the Moon, we have two very useful pieces of information. First, if the time of occultation is known to one second, then we can fix an arc relative to the star field with a precision of half a second of arc (if the experiment is repeated, the intersection of the arcs fixes the source position with this precision); and secondly, we have a scan across the source, which, depending on the time resolution, may reveal its size and structure. My purpose in this talk is to explain the cyclic way in which these occultations occur so that you may become more aware of future possibilities for using this technique on X-ray sources.

The Moon's orbital plane is inclined at 5° 9′ to the ecliptic. In any one orbit round the Earth the Moon's disk obscures a thin band with a width of two and a half degrees, being twice its horizontal parallax plus semi-diameter. The nodes of the intersection of its orbital plane on the ecliptic regress in a period of 18·6 years, so that in this period the Moon's orbital plane sweeps out a band 10° 18′ wide, centred on the ecliptic. This band is further extended to about 13 degrees by parallax, semi-diameter and perturbations in the mean inclination of the orbit. Scorpio X–1 and the Crab Nebula (to mention two) lie within this band.

By coincidence, the galactic plane (inclined at 61° to the ecliptic) intersects the ecliptic at 18 hours right ascension, −23·4 degrees declination, which means that the galactic centre lies about 1° inside the lower limit of the occultation band and, since a number of the strong galactic sources lies in this direction, they will be liable to occultation some time during the 18·6 year cycle. If we now concentrate on this region near the galactic centre, from what I have already said, you will see that the Moon's orbital plane (effectively 2·5 degrees wide) oscillates across this region near 18 hours between the declination limits −29·9 and −16·9 degrees. The Moon's orbit was at the lower limit around 1970·3 and will reach the upper limit about 1979·6. Thus the Moon has recently completed a series of occultations of the galactic centre and the last occultation at present of GX3+1 occurs in October 1972. GX5−1 begins a series of occultations in May 1972 and GX9+1 begins in November 1974.

To visualize how the occultation of a particular source seems to an observer near the Earth's surface, imagine parallel rays from the source arriving at the Moon, which then produces a cylindrical "shadow" towards the Earth. As the Moon moves across the source, the "shadow" (whose diameter is a quarter of the Earth's) traverses the Earth from west to east in about three hours, at a velocity of 4000 kilometres per hour. As the plane of the Moon's orbit moves up across the sources near the galactic centre, and the Moon traverses its orbit, the "shadow" first touches the Earth at the South Pole and then, in successive months, passes farther north until it touches the North Pole about two years, or about 25 lunations, later.

The possibility emerges of using an orbiting satellite, such as UK5, to observe such occultations since its orbit is very likely to intersect some of these comparatively large shadow bands traversing the Earth. One disadvantage over a rocket-borne experiment is that, given the same sensitivity of detector, the rapid motion of the satellite relative to the shadow will reduce the resolving power of an occultation observation by a factor of about four.

Professor Hutchinson. How accurately do you know the figure of the Moon and does not this set a limit on the accuracy of the deduced positions?

Mr. Morrison. The marginal region is known to about one-fifth of a second of arc so this is not really a limitation here. Of course the satellite's position relative to the centre of mass of the Earth has to be known to the order of two kilometres to achieve a second of arc precision in the deduced source position.

Dr. A. Hunter. What fraction of the sky is covered by the occultation band and does this give you the proportion of sources you can investigate this way?

Mr. Morrison. About one-tenth; but since many of the sources are concentrated towards the galactic centre, which lies in the occultation band, a relatively high proportion is occulted.

Dr. Mackay. Would not a satellite in an highly elliptical polar orbit maximize the parallactic broadening of the occultation band and also reduce the speed of occultation?

Mr. Morrison. Yes. I believe that ESRO proposed launching a satellite deep enough into space so that it would see the Moon projected against a wide region of the sky.

Dr. Pounds. A satellite launched to 200,000 kilometres and out of the plane of the ecliptic was proposed by ESRO. Sources would be fixed typically to one arc second—the limitation is knowledge of the satellite's position to about one kilometre. The position of UK5 will certainly be known with better accuracy than this.

Mr. C. A. Murray. The accuracy of the optical positions which are to be compared with the X-ray positions has not been mentioned so far. They can be determined to about one-fifth of a second of arc, which is comparable to some of the other errors discussed.

Professor Hutchinson. Now it is time to proceed with the next paper, which is by Dr. Culhane and is entitled "The X-ray astronomy programme at the Mullard Space Science Laboratory".

Dr. J. L. Culhane (Mullard Space Science Laboratory). While in the past much of our effort has gone into studies of the solar X-ray spectrum, we have in the last few years undertaken a considerable programme of cosmic

X-ray astronomy. In 1970, before the launching of UHURU, a rocket-borne large-area proportional counter observed the Cygnus X–1 source twice during its flight. Pulsation was detected in the first observation with a period of 115·8 milliseconds but when the source was scanned again 95 seconds later, there was no detectable pulsation. We now know from the UHURU observations that these two results are consistent with a fluctuating source with a wide range of pulsation frequencies. We are developing a high-time-resolution (3–4 microseconds) X-ray detecting system to study the Centaurus X–3 source early next year. It is possible that the data obtained with this system will allow us to differentiate between the models that have been put forward to explain the behaviour of this source.

A large-area counter experiment was flown in 1970 to search for fluctuations in the diffuse X-ray background in the 1–10 keV energy range. The detector looked at nine different parts of the sky known to be free of identified discrete sources. The fluctuation in intensity over the nine regions was less than four per cent. Each region was about 72 square degrees in size. A simple analysis, which assumed all the sources to have equal apparent brightness, established a lower limit of 400,000 sources in 4π steradians if the diffuse component were due to radiation from unresolved sources. It is planned to repeat this experiment later this year in a different part of the sky.

Very recently an opportunity occurred to observe a lunar eclipse of the galactic X-ray source GX3+1 from Woomera in South Australia. The MSSL group instrumented the second of two rockets flown to carry out this observation. By combining our result with that of the Leicester University group, it was possible to place the source in an error box of 1 by 25 seconds of arc. It is hoped to refine this observation further with a satellite-borne instrument in the not-too-distant future.

I have been associated with the X-ray astronomy group at the Lockheed Palo Alto Laboratory who have recently carried out a soft X-ray observation of the Virgo Cluster. They observed an extended source of about 0°·5 diameter and a turnover in the spectral phase at low energies. One interpretation would suggest a large amount of material contained in the source.

Much of our present programme involves observations in the low-energy X-ray range (0·1 to 2·0 keV). There is considerable controversy at present as to the origin of the soft X-ray background flux. We plan to repeat a crucial experiment in this area by searching for absorption of the diffuse X-rays in the Small Magellanic Cloud. The present result, obtained by a group at the University of Wisconsin, is consistent with less than 25 per cent of the radiation originating behind the galaxy. Should the radiation originate in our Galaxy, it will be necessary to establish its source. In this connection, we intend to examine the radio continuum loops for evidence of soft X-ray emission. Finally we plan to search for *O* VII and *O* VIII line emission from one of the older supernova remnants in an attempt to verify the existence of a shock-heated plasma in the source as predicted by the work of Shklovskii.

In addition to the observational X-ray astronomy, a considerable effort is being made to develop position-sensitive X-ray detectors which will be used to register the images formed by grazing-incidence X-ray telescopes. A number of very promising schemes, which we hope will be used at the focal planes of the large X-ray telescopes of the future, is being investigated.

Dr. Rowan-Robinson. Have you got a flux density for M87?

Dr. Culhane. Yes. Our flux density is about half that found by UHURU; this is because we see only the central half-degree of an extended source.

Dr. Pounds. If the absorbing gas which you mentioned is in the Virgo cluster, the mass will be quite large. However, fitting the data with a bremsstrahlung curve would give a natural turnover and greatly reduce the need for an absorbing gas. One finds that the UHURU data can be fitted with a less steep power law, with an index of 2·7 instead of 3·4, or with a mixture of thermal sources, both of which give a lower column density.

Dr. Culhane. That is quite true; those possibilities must be considered.

Dr. Pounds. It is particularly interesting that you do not find anything at one-tenth degree resolution—does that mean that the source is uniformly bright?

Dr. Culhane. It is not quite so clear cut—our data would be consistent with an unresolved point component up to 30 per cent of the total.

Dr. Hutchinson. In view of yesterday's comment from Dr. Pounds on gamma-ray statistics, I think you should argue about this in private! We must ask Dr. Sciama to come forward with the next paper—"X-ray emission from the neighbourhood of galaxies".

Dr. D. W. Sciama (University of Oxford). The work I am going to describe was carried out in collaboration with Dr. Roland Hunt. It deals with a problem which has concerned me for over twenty years, namely, the existence and properties of the intergalactic medium. Its density is of particular importance since, as is well known, the total amount of matter in the intergalactic medium could exceed that in galaxies by a factor of ten, in which case it would have a dominating influence on the dynamics of the expanding universe. Such a gas would be hard to detect if it had an elevated temperature of, say, a million degrees. Moreover, there is no energetic problem in heating the gas to this temperature by means of emanations from galaxies, radio galaxies or quasars.

There is one particular way in which such a hot extended gas could be detected, and that is from its soft X-ray bremsstrahlung. In fact, existing X-ray detectors could easily observe flux from a gas at a million degrees if its emission measure $\int n_e^2 dl$ is only 0·3 cm^{-6} parsec, about a hundred times less than the emission measures that can be detected optically or in the radio region (for a gas at ten thousand degrees). As Dr. Culhane mentioned, there is indeed believed to be an excess soft X-ray component of the diffuse background, which would require an emission measure of this order. Friedman and his colleagues originally proposed that its source was a hot universal intergalactic gas with n_e about 10^{-5} per c.c. and l about 3×10^9 parsecs. This would correspond to the magic density associated with the Einstein–de Sitter model, which occupies the dividing line between the ever-expanding and the recontracting universes.

Unfortunately there are other ways of obtaining an emission measure of 0·3 cm^{-6} parsec. The one I am concerned with today is based on a gas with n_e about $1 \cdot 7 \times 10^{-3}$ per c.c. and l about 10^5 parsecs, comprising a halo around our Galaxy. We envisage this halo as arising by accretion of intergalactic gas in the Local Group of galaxies, rather than from an outward wind as originally proposed by Spitzer and recently reconsidered by various authors. For this accretion problem it is necessary to describe the motion of the intergalactic gas by fluid-mechanical equations, and we have used for this purpose the recent numerical computations published by Dr. Hunt in volume 154 of the *Monthly Notices*. Our calculations show that the excess soft X-ray background can be accounted for if the initial density and temperature of the Local Group gas are 3×10^{-4} per c.c. and 500,000 degrees, in reasonable agreement with the original parameters proposed by Kahn and Woltjer.

This proposal could be distinguished from the truly cosmological explanation in several ways. First, because of our eccentric position in the Galaxy the X-ray halo would appear to be markedly anisotropic. Secondly, the Magellanic Clouds would be less absorbing on our hypothesis. Thirdly, there may be detectable soft X-ray lines emitted by heavy elements that have been able to reach the periphery of the Galaxy from supernova explosions. The discovery of such lines would show that a differential red shift, associated with the expansion of the universe, is not in operation.

We have also carried out similar calculations for external galaxies, in particular M31 and M87. The results for M31 show that the Kahn–Woltjer parameters would lead to an observable X-ray halo around that galaxy. The results for M87 are of more immediate interest since it is already known to be an extended X-ray source, as you have just heard from Dr. Pounds and Dr. Culhane. M87 is also of special interest because its mass may be a hundred times greater than that of our own Galaxy, in which case the accretion effects would be much stronger. In fact our calculations agree well with the most recent observations if the initial density and temperature of the gas in the Virgo cluster are 5×10^{-5} per c.c. and 3,000,000 degrees. Further measurements of the spectrum and angular distribution of the soft X-ray flux would provide a decisive test, and so may at last lead to the definite observation of a gas in intergalactic space.

Professor Hutchinson. Do the Magellanic Clouds distort the spherical symmetry of the accretion process?

Dr. Sciama. Not significantly. Nevertheless, important observational effects might be produced by absorption by neutral hydrogen in the Clouds, or by the emission of X-rays from sources within them.

Dr. Pacini. Would the rotation of the Galaxy affect the accretion process?

Dr. Sciama. Our calculations show that the X-ray emission is almost independent of the distribution of mass assumed in the Galaxy, whether we adopt a point mass at the centre or a more realistic disk. While we did not try the effect of a rotating galaxy, these results from the mass distribution lead me to think that rotation would not make a large effect.

Professor Lynden-Bell. Surely the important rotation is that of the intergalactic medium, and that rotation would be magnified during the accretion?

Dr. Sciama. That is true. However, we know nothing about the vorticity of the intergalactic medium. Certainly one must be careful not to accrete too much angular momentum, as this might destroy the observed co-rotation of the gas and the stars in the galactic disk. It may be that the pressure of the disk gas reduces and controls the accretion, and that this pressure is in turn controlled by the accretion.

Professor Cowling. Would not the inflow of matter prevent the outward diffusion of heavy elements generated in the Galaxy?

Dr. Sciama. That is quite probably true at considerable distances from the disk, but it need not be true in the first few kiloparsecs where the inflowing velocity may be rather small.

Professor Cowling. This process could also prevent the escape of low-energy cosmic rays from the Galaxy, if a magnetic field were trapped in the inward-moving matter.

Dr. Sciama. Yes. The problem of the leakage of cosmic rays from the disk would have to be reconsidered if accretion is occurring. I might add that in calculating the equivalent widths of the lines, we assumed that local thermodynamic equilibrium applies, but in fact the inflow time might be too short for that to be so.

Dr. Culhane. Could a galactic "wind" produce X-ray emission at a similar level?

Dr. Sciama. Burke and Hartwick have considered X-ray emission from a wind powered by violent events in the Galactic nucleus. In such a case, the heavy-element concentration would probably be large, and the line emission would dominate over the continuum.

Mr. Fabian. How does the model explain the soft X-ray excess in the plane, in view of absorption?

Dr. Sciama. I should attribute the excess at low latitude to discrete sources.

Dr. Mackay. With a very broad line such as you mention, a fairly large red shift range could be tolerated before the line would smear out substantially. Would this not make local and cosmological origins difficult to distinguish?

Dr. Sciama. No, the breadth is the equivalent width, not the actual width. A high enough spectral resolution would make the distinction possible.

Professor Hutchinson. Our next paper, entitled "The origin of the soft X-ray background", is from Mr. A. C. Fabian.

Mr. A. C. Fabian (Mullard Space Science Laboratory). We have studied current observations of the soft X-ray background and deduced that a predominantly galactic origin is suitable for their explanation. In general, experiments tend to show that any correlation of absorption of an extragalactic component by interstellar hydrogen with galactic latitude fails at galactic latitudes less than about 30 degrees. The level of the soft X-ray flux in the galactic plane does suggest a galactic component.

We have investigated a model consisting of an exponential distribution of sources, whose flux is absorbed by an exponential distribution of hydrogen. The scale height of this hydrogen distribution is taken as 100 parsecs for low galactic latitudes, but varied to agree with 21-centimetre column-density measurements at higher latitudes. When the soft X-ray flux from this model is added to an extragalactic component attenuated by the hydrogen, the source scale height has to be about 100 to 150 parsecs in order to agree with the observational variation with latitude. It is then not necessary to conclude that there is any excess extragalactic flux over an extrapolated power law, as seen at higher energies. Suitable source models may be those in which the interstellar gas plays a dominant part, since the two scale heights are similar. Possibilities are supernova remnants or accretion by old neutron stars.

Dr. Hillier. How diffuse would the background be? How many supernovae and neutron stars are there?

Mr. Fabian. I should refer you to a recent paper by Mack in *Nature.* One difficulty is that scattering affects the non-uniformity of the sky brightness that one would expect from the numbers of discrete sources.

Dr. Culhane. The American Science and Engineering group have data from a recent flight which show that the diffuse background fluctuates at the 14 per cent level at energies below 2 keV. Our model of a galactic component which contributes to the low-energy background does limit the excess at high galactic latitudes to less than 30 per cent of the observed signal at 0·25 keV.

Professor Lynden-Bell. Murray's work on very late-spectral-type stars near the Sun shows a scale height very similar to the one you require. I think that many of these stars are flare stars—could they produce these X-rays?

Dr. A. H. Lategan. I am going to speak on that subject this afternoon.

Professor Hutchinson. If there are no further questions, let us ask Mr. J. C. Brown, who is the last speaker in this session, to present his paper on "The polarization and directivity of thick-target bremsstrahlung X-ray sources".

Mr. J. C. Brown (Glasgow). In thermal X-ray sources heated to temperature T by non-thermal electrons, such as Pacini and others have mentioned, non-thermal bremsstrahlung must dominate at energies well above kT. Thus, the detailed theory and observations of non-thermal bremsstrahlung from solar flares may clarify cosmic mechanisms generally and flare stars particularly. Nevertheless, the continuing lack of an adequate theory of flares, despite the wealth of data, is a caution against over-simple models of cosmic sources. Even X-ray polarization measurements are not unambiguous diagnostics of X-ray flare conditions, as I will shortly show. I doubt whether even the elliptical and plane polarization, characteristic of synchrotron and bremsstrahlung sources respectively, are in practice distinctive of cosmic mechanisms. The phase data necessary for this distinction are lost at energies above a few keV since polarimeters operate by scattering methods in this range.

According to Takakura's hard X-ray flare model, electrons are impulsively accelerated in a coronal magnetic trap and are subsequently collisionally degraded. Alternatively, electrons may be injected continuously into the dense chromosphere by an acceleration mechanism which therefore determines the time profile of the burst. Since attempts to distinguish these models using geometrical and spectral arguments have failed, their polarization and directivity are currently of interest.

Analyses of the predicted and observed directivity of these models by Ohki and by Pinter, claimed to establish the Takakura model, have been discounted by Drake on observational grounds. Also, these authors have oversimplified the models theoretically by neglecting magnetic field curvature, electron spiralling and electron scattering. Detailed computations of both models are thus necessary before we can properly compare their polarization P and directivity D with observations. I have considered P and D for a model in which electrons with a power-law energy spectrum are injected continuously down a vertical field, as in Sturrock's flare model. An analytical description of the thick-target scattering and fully-relativistic bremsstrahlung cross-sections were incorporated in the necessary triple integrations over electron velocity and depth in the chromosphere. The computations predicted P and D (as functions of the burst's heliocentric angular distance) at 10,50 and 150 keV photon energies. Bursts are expected to be limb-brightened, especially at high photon energies, the brightening below 10 keV being within Drake's observational limits. The degree of polarization P is predicted to increase from zero at the disk centre to about 35 per cent at the

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limb. Recent polarization observations from Intercosmos 1 by Tindo and others are consistent with this, though far from definitive.

Unfortunately, Haug has found roughly similar predictions for the Takakura model except that the plane of maximum polarization is tangential to the disk in this model whereas it is radial in the above study. However, the only observations of this plane are not definitive, owing to rotation of Intercosmos 1. In any case, if the actual flare field deviates much from the idealizations in these computations, then distinction of the models might demand magnetograms of the X-ray flare in its flash phase!

Dr. Culhane. In fact, observations of high-energy X-rays from flares are contaminated by soft X-rays from plasma. Could not the variation of polarization in a flare be due to this contamination? One needs data that refer only to energies above 20 keV.

Mr. Brown. That is a valid point but can only partly explain the observations. Might I repeat my problem, for cosmic sources, of how to look for elliptical X-ray polarization? Has anyone any ideas on how to do that?

[The next session was chaired by Dr. A. H. Gabriel. The first paper was by Dr. D. Ramsden on "Evidence for point sources of high energy gamma radiation". Dr. Gabriel then gave his own contribution on "Dielectronic Recombination Satellite spectra".]

Dr. Gabriel. I would like to speak briefly about some computations I have been carrying out recently, which, although motivated by solar-flare X-ray spectra, will become increasingly relevant to cosmic X-ray spectra as the observing techniques improve. These are concerned with the close group of lines alongside the helium-like ion resonance line in highly-charged ions. This group includes not only the intercombination and forbidden lines of the helium-like ions, but also the inner-shell transitions in lithium-like ions, produced primarily through the process of dielectronic recombination.

I have been calculating the wavelengths and intensities of the lithium-like members of this group, allowing both for dielectronic recombination and direct inner-shell excitation as production mechanisms. These calculations are carried along the isoelectronic sequence from carbon to copper. The method follows that used earlier for low atomic-number ions by Carole Jordan, Paget and myself. However, whereas for low atomic numbers some simplifications in the theory are possible, at higher numbers it is necessary to work in intermediate coupling and to derive values for the auto-ionizing rate of each level concerned.

The slide shows a computed spectrum for iron superimposed on an observed spectrum of a solar flare taken by Zitnik and his collaborators. It shows about four inner-shell lithium-like lines, and about three helium-like lines (one or two are probably blended) between 1·85 and 1·87 ångströms. The relative intensities in the helium-like lines can be used to derive electron densities using the theory of Gabriel and Jordan, provided the densities are sufficiently high. The relative intensities of some of the lithium-like lines to the helium-like resonance line depends on electron temperature, according to the present calculations. However, some of the lithium-like lines have appreciable contributions from direct inner-shell excitation. Their intensities then depend also on the relative populations of ion stages. Measurements on this group can therefore in principle give the electron density, electron temperature and transient ionization state of the plasma.

In cosmic sources, present observational techniques have not yet succeeded in resolving the combined iron feature, let alone the individual lines. However, in considering models for objects like Scorpio X–1 it is important to note the complexity of the feature and the fact that the optical thickness of the lines varies greatly, being much smaller for $1s^2\,{}^1S - 1s2s\,{}^3S$ and $1s^2\,2p - 1s\,2p^2$ lines than for the others.

[Dr. Gabriel then introduced Dr. R. G. Bingham, who delivered the next paper entitled "The distribution of X-ray sources in the Galaxy".]

Dr. R. G. Bingham (Royal Greenwich Observatory). It may be interesting to see whether the positions of the X-ray sources from the second edition of the UHURU catalogue broadly coincide with large concentrations of matter and identifiable features of the Galaxy. Comparing possible groups of X-ray sources with the maxima of 21-centimetre emission, thermal radio emission and groups of radio sources along the galactic equator, there are only two coincidences; they are possible relationships of groups of three X-ray sources with thermal radio emission near longitudes 290 and 340 degrees. The relevant sources have galactic latitudes of less than half a degree. Apart from those, one would conclude that the majority of the sources is not related to a "spiral arm" population.

The general distribution of the sources in longitude has some resemblance to the large-scale thermal radio emission, and both could represent the projected effect of a ring of appropriate sources in the Galaxy. However, the X-ray sources are much more widely spread in galactic latitude. Comparison of the X-ray positions with the non-thermal radio emissivity of the Galaxy may also be made. A possible distribution of relativistic electrons may be found by dividing the non-thermal emissivity by $B^{1.7}$, where the magnetic flux density B is estimated for different regions of the Galaxy using a dimensional method due to Lynden-Bell. This shows that the relativistic electrons are more numerous in a band in the Galaxy, at a radius of 2·5 to 4·5 kiloparsecs, which might perhaps represent a "supernova belt". The X-ray sources appear to fit this belt only weakly when one studies the longitude distribution, but the widths of the distributions in latitude agree well.

In comparing the distribution of X-ray sources with that of various types of star, one may notice that 65 per cent (36) of the sources with galactic latitude of less than ten degrees lie within forty degrees of the galactic centre. The median latitude of these 36 sources is 2·5 degrees. A model which fits this distribution reasonably well is one which contains the sources in a slab 6 kiloparsecs in diameter and 800 parsecs thick between median planes, with also some central concentration. The typical z distance of 400 parsecs corresponds to an "old disk" population (also consistent with the central concentration), and applies to old novae and pulsars, for example. For comparison, stars near the Sun with such a distribution in z have ultraviolet excesses of approximately one-tenth of a magnitude. This corresponds to an iron deficiency with respect to the Sun by a factor 2·5. Perhaps such a deficiency will help to explain the weak iron line in the spectrum of Scorpio X–1 mentioned by Dr. Pounds yesterday.

Dr. Gabriel. Are there any questions? Well, the next paper is from Dr. A. H. Lategan and is on "Expected X-radiation from flare stars".

Dr. A. H. Lategan (University of Sussex). There is reason to believe that flare stars are sources of X-ray emission. On the basis of an analogy between optical flares on the Sun and stars of the UV Ceti type, simultaneous radio flares were predicted and observed in 1958. This raises hopes of observing the expected simultaneous X-ray emission.

Attempts to estimate the expected flux have been made by Grindlay and by Gurzadyan on the assumption that X-radiations from these stars are the result of the conversion of the energy of "fast electrons" into photons by some process or other. Grindlay estimated the energy and number-density of the electrons involved, which are compatible with the data obtained from observed radio and optical flares, on the assumptions that the radio emission is of synchrotron origin and that the electron spectrum follows a power law. He used this to arrive at an estimate of 3×10^{31} ergs per second for the expected X-ray energy flux from photons of energy greater than 10 keV from UV Ceti as a result of non-thermal bremsstrahlung of near-relativistic electrons.

Gurzadyan points out that Grindlay neglected the effect of self-absorption when using the observed radio emission to calculate the density of the high-energy electrons involved, and derives his own expression for the X-ray flux during a flare based on his own model of UV Ceti type flares. This assumes that an envelope of fast electrons round the star produces all three types of emission, optical emission from free-free transitions, radio emission from synchrotron radiation and X-radiation from non-thermal bremsstrahlung. By noting that an energy of 1·5 MeV for the electrons makes this model consistent with the observed optical and radio fluxes during flares, the appropriate expression for the non-thermal bremsstrahlung can be used to estimate the X-ray flux.

Mack has recently considered various sources possibly responsible for the galactic flux of soft X-rays. From recent observations he derives a value of 2·6 or $7{\cdot}0 \times 10^{-28}$ ergs per c.c. per second for the total power radiated per c.c. in the energy interval 0·28–0·8 keV, depending on whether interstellar extinction by clouds of hydrogen is taken into account or not. On the basis of Grindlay's estimates, Cavallo and Horstman recently concluded that flare stars in the solar neighbourhood might be the chief sources of the diffuse soft X-ray background. However, Grindlay's estimate was made for hard X-rays and has been criticized by Gurzadyan, so that I considered it worth while to check Cavallo and Horstman's conclusion. Accepting Gurzadyan's expression for the flux of X-rays with a given energy at its face value, I first integrated it in the energy region concerned (0·28–0·8 keV). The radius of the star and the magnitude of the flare appears in Gurzadyan's expression. As I did not have sufficient data on the distribution of flare magnitudes for all flare stars in the solar neighbourhood, I decided to obtain an upper limit to their expected X-radiation by considering all flare stars as being similar to the most active one, namely UV Ceti. I could then use Gurzadyan's analysis of the data obtained from over 900 flares to integrate over flares of different magnitude and obtain a time average. The result of these calculations gives an expected average X-ray energy flux density from flare stars of 4×10^{-30} ergs per c.c. per second, some 100 times smaller than the observed flux.

I have to stress that the above answer is very model-dependent, and one cannot be too confident about the extrapolation of data on the optical and radio flux to obtain an X-ray flux. The only warranted conclusion is that the calculations tend to show that, *contra* Cavallo and Horstman, flare stars are not the most important contributors to the diffuse X-ray background, but that the possibility of their being so is not definitely ruled out. Owing to the uncertainty of present theoretical predictions, this question can only really be settled by direct observation.

Mr. J. C. Brown. Calculations on models of solar flares show that an electron beam producing a fixed X-ray flux can result in a very wide range of $H\alpha$ emission by heating a variable chromospheric area. This means that an observed optical flux in a flare star may correspond to a wide range of predicted X-ray intensities. Gurzadyan adopts a one MeV mono-energetic electron beam. Does he includes the electron–electron bremsstrahlung which totally dominates the electron–proton bremsstrahlung at this energy? If not, his X-ray flux estimate should be much increased, and it would be more plausible that flare stars contribute to the background.

Dr. Lategan. Yes, he does. Of course, this is a very tentative calculation. Grindlay obtained roughly the same figure for the X-ray flux in a flare as Gurzadyan, by a different method. In so far as these two tentative methods agree, I think one can have a little more confidence in the final figure.

Dr. Gabriel. By analogy with solar flares, you might expect to see low-energy line emission.

Dr. Lategan. Yes. However, there are significant differences in the amount of energy concerned in solar and stellar flares, and in the ratio of radio to optical fluxes, so the analogy can't be taken absolutely literally.

Dr. Gabriel. Thank you, Dr. Lategan. Let us proceed now to Dr. Pagel's paper, which is on "Possible coronal lines from Eta Carinae".

Dr. B. E. J. Pagel (Royal Greenwich Observatory). The nova-like variable η Carinae is probably the most luminous known star in our Galaxy, though its appearance is non-stellar. Its visible spectrum consists of emission lines, with profiles suggesting rapid expansion, superposed on a continuum which at first sight looks non-thermal; but relative strengths of hydrogen and permitted and forbidden *Fe* II lines at different wavelengths imply that there is internal reddening as well as the normal interstellar reddening. If this reddening (with accompanying absorption) applies to the continuum it turns out to match the spectrum of a black body at about 30,000 degrees, with a luminosity of the right order of magnitude to supply the enormous amount of infra-red radiation observed by re-emission from a surrounding dust cloud. Assuming that the visible radiation comes from a hot, massive central star, Kris Davidson has proposed a model of the visible nebulosity as a photo-ionized *H* II region.

A Livermore survey of the southern Milky Way has detected η Carinae as a soft, apparently thermal, X-ray source with electron temperature between about 2·5 and 3·7 million degrees, and Davidson and Ostriker have explained this by postulating that the expanding visible nebulosity shock-heats a fairly dense surrounding medium to this range of temperatures leaving a compressed region with an electron density around 8000 per c.c. and a volume V such that $N_e^2 V$ is about 10^{59} cm^{-3} to account for the X-ray flux at an assumed distance of 2 kiloparsecs. These model parameters are in the range where one might expect to see coronal lines in the optical spectrum.

The strongest visible line to be expected is the green line of forbidden *Fe* XIV, which should be observed with a flux of at least one per cent of that in $H\beta$ provided that the temperature is less than 2·6 million degrees and that the X-ray emitting region is affected by interstellar absorption of about 1·5 magnitudes only. This flux is near the sensitivity limit of line lists by Aller and by Thackeray, in neither of which the green line appears. There is, however, an unidentified line in Thackeray's list at wavelength 3388·41, very close to forbidden *Fe* XIII at 3388·5. Bearing in mind the higher sensitivity in the ultra-violet, and the fact that 3388 is sometimes almost as strong as the green line in the solar corona, the identification of 3388 with the forbidden *Fe* XIII transition is not impossible. If it is correct, we should expect the green line to appear on spectra taken at 15 ångströms per millimetre in the visible, and if this prediction should be verified it will provide confirmation of the Davidson–Ostriker model and a more accurate estimate of the temperature in the shock-heated region.

Dr. C. Jordan. The other ion which is likely to produce observable lines is *Fe* XII, if that temperature range is about right. In fact, there is a line at 3072 ångströms. Did Thackeray's spectra extend as far as that?

Dr. Pagel. No. The region should be looked at by satellite.

Dr. Gabriel. Are there density-dependent terms in the intensities of these lines?

Dr. Pagel. No; at such low densities, the relative intensities are almost independent of density.

Dr. Webster. Does the 3388 line stand out by itself in the spectrum? If there are no strong lines nearby, can one predict what a picture taken at this wavelength would look like? Would it show a shell structure?

Dr. Pagel. That's a fascinating thought. I think that the line is certainly separate in a coudé spectrum, but it might be tricky to get an interference filter with no leaks to other lines.

Dr. Gabriel. Have you considered the idea that Eta Carinae may not be in ionization equilibrium *because* it is an expanding source?

Dr. Pagel. I assumed a steady state at a particular electron temperature. Probably the expansion time-scale is long compared with the time for equilibrium to be established. But one should check that carefully*.

Dr. Gabriel. Dr. Webster would like to say a few words about a possible optical identification of an X-ray source.

Dr. Webster. I want to point out an emission-line star, H 177, which lies about 2σ away from the UHURU X-ray position of 2ASE1639–62. The star shows the strong hydrogen, helium and forbidden lines seen in planetary nebulae, and fainter permitted and forbidden lines of ionized metals, superposed on a faint continuum. The temperature and density are high relative to nebulae, and the Balmer lines may be self-absorbed. The radial velocity and galactic latitude place the object in the old disk or halo population. The $H\alpha$ line profile has a strong central core and wide wings, which are asymmetrical and therefore probably cannot be explained as being due to electron scattering. Accordingly, there is evidence of gas velocities in or near the star of some thousands of kilometres per second which, if converted to thermal energy, could give rise to X-radiation. One might, therefore, expect this star to be an X-ray source and I would welcome other people's

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*Dr. Pagel stated later that with a collisional ionization rate constant at 10^{-9} cm^3 sec^{-1}, the time for ionization equilibrium to be established is about 10^6 seconds, compared to expansion and cooling time scales of the order of 100 years—EDITOR.

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comments on whether the X-ray position is well enough defined for the identification to be unlikely.

Mr. Cruise. The X-ray source is weak and of course there is more trouble fitting the overlays on the different scans for weak sources than for strong. The error boxes are at the 90 per cent level of significance so even statistically there is a fair chance of some sources being just outside the boxes.

Dr. Gabriel. Could the UHURU group repeat a positional analysis to see if a particular optical object is in fact a possible candidate?

Mr. Cruise. One imagines so.

Professor Lynden-Bell. Is the star a radio source in the Parkes catalogue?

Dr. Webster. No, but the cut-off limit of survey catalogues is quite high—one flux unit.

Dr. Jackson. If you interpret the broad wings of $H\alpha$ as a temperature does this tie in well with the X-ray spectrum?

Dr. Webster. The only measurements of the flux are from UHURU. There are no published spectral data. The wings are compatible with a high temperature.

Dr. Jackson. Would the temperature be so high as to suggest a hard thermal bremsstrahlung spectrum?

Dr. Webster. Yes.

Dr. Fabian. Is the star unique optically?

Dr. Webster. I know of no stars exactly like it, but it has spectroscopic features in common with slow novae, like RR Telescopii, and according to Feast also with symbiotic stars. There are no detected X-ray sources near either RR Telescopii or any of the other symbiotic stars but none of these has wide wings on $H\alpha$.

Dr. Gabriel. Well, that is the end of the Conference.