THEORIES OF DISCRETE X-RAY AND γ-RAY SOURCES

(Invited Discourse)

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Abstract. This is a critical review of theories of known discrete X-ray sources. The Crab is omitted, having been dealt with in Woltjer's review. Two of the identified sources, Sco X-1 and Cyg X-2, seem to be of the same sort. A binary or gas-stream model like that of Prendergast and Burbidge, with dimension $R \sim 10^9$ cm and density $n \sim 10^{16}$ cm^{-3}, appears reconcilable with the observed features of these sources, though much detailed work remains to be done. Neither object is yet known to be binary. Theoretical work becomes more difficult if, as appears to be the case at least for Sco X-1, the objects are optically thick due to electron scattering; this may affect the optical and X-ray spectra.

The recent searches for iron lines in the X-ray spectrum of Sco X-1 are reviewed briefly. The calculations and the energy resolution are not yet good enough to make this a dependable test of models.

Several possibilities are offered for explaining the excess radio flux from Sco X-1.

Other theories of Sco X-1-type sources are discussed briefly. The theory of Manley and Olbert seems a little superfluous when the gas-stream theory is still in a strong position.

There are serious discrepancies between X-ray and optical estimates of the distance to Sco X-1. 21-cm measurements must also be considered. The situation is reviewed, and ways out of the difficulty are discussed.

Cen X-2 seems to be like Sco X-1, but several other unidentified sources have hard spectra like the Crab. It is tempting to speculate that most of the galactic sources are supernova remnants.

The extended γ-ray source in the galactic plane may be the extrapolated unresolved sum of galactic X-ray sources, as suggested by Ogelman. There are several other possibilities.

M87 is the only established extragalactic source. Radio, optical and X-ray observations are summarized and graphed. A power-law extrapolation to the X-ray band is far from mandatory; nevertheless the optical flux from the jet is known to be synchrotron radiation. The time-scale difficulties in the jet are described, and several theories of the survival of the optical electrons are reviewed.

Processes for producing X-rays other than thermal bremsstrahlung and synchrotron radiation are listed. These other processes are characterized by low efficiency, and are likely to be unimportant in discrete sources, though several have attracted attention with reference to the diffuse background.

1. Introduction

The first thing to be said is that I am essentially a novice at this subject. Most of my own work in X-ray astronomy has been concerned with the cosmic background rather than with discrete sources. Consequently I have had to work pretty hard to prepare this review, but let us hope that I have brought to it the characteristic virtues of the amateur. Those who find my conclusions naive may take comfort; they may well be right!

Let me try to indicate briefly what I shall do and not do. I *will not* try to develop 'theories' of each object by just collecting and repeating the data we have heard reported. Nor will I deal with the newly found X-ray pulsar in the Crab, the theory of which is too young to admit useful review, and really belongs in a pulsar conference anyway. Instead I shall confine myself to discussing the prototype objects, starting

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with Sco X-1 and bringing in data from Cyg X-2, which seems to be similar in most ways. The other prototype of galactic sources is the Crab, but I am leaving discussion of this entirely to Professor Woltjer, to avoid needless duplication. I shall speculate a little on the nature of the many unidentified galactic sources and add some remarks about γ-ray sources and particularly possible sources in the galactic plane. Then I shall move on to the extragalactic sources, M87 being the only one of these which can bear much comment, and, judging by reports here, the only one which is well established. Finally I shall discuss some of the 'exotic' processes of photon production which have been suggested but are not known to be important in any observed source.

2. Scorpius X-1

This is of course the prototype of the thermal objects. Its identification by Giacconi, Sandage and coworkers (Sandage *et al.*, 1966) was a milestone in astronomy, made possible by the accurate X-ray position; we need more such positions. Its optical properties (Johnson *et al.*, 1967; Westphal *et al.*, 1968; Johnson, 1968; Neugebauer *et al.*, 1969) are by now familiar: a blue continuum, only slightly polarized (Hiltner *et al.*, 1967), variable in time, accompanied by emission lines of both low and high excitation which suggest a wide range of temperature within the source. The emission lines also seem to vary in intensity. The line wavelengths vary irregularly, suggesting gas streams of some sort; sometimes different lines seem to move in antiphase, but no regular period has been established, so the object is not, as of now, a spectroscopic binary. The same is true of Cyg X-2 (Kraft and Demoulin, 1967; Kraft and Miller, 1969) where the emission lines are accompanied by many stellar absorption lines. Although no period has been established for either object, the spectra are complicated, and one still suspects that binary motions or even multiple systems might be present.

It was realized early that the X-ray spectrum of Sco X-1 is nicely fitted by an exponential curve for optically thin thermal bremsstrahlung, with $T \approx 5 \times 10^7$ K. More recently it has been confirmed that this best-fit T varies (Gorenstein *et al.*, 1968; Chodil *et al.*, 1968), and also that there is at high photon energies a nonthermal tail (Peterson and Jacobson, 1966; Buselli *et al.*, 1968), apparently also variable (Lewin *et al.*, 1968a; Overbeck and Tananbaum, 1968; Riegler, 1969). There is a correlation between the optical continuum brightness and the temperature of the thermal X-ray curve, but its nature is in doubt. I shall return briefly to these variations later.

3. A Binary Model

The distance D to Sco X-1 was first estimated as 100–1000 pc, by analogy with the old novae which it resembled. Even this rough estimate was useful because, with the bremsstrahlung nature of the source established, it made possible an estimate of $\langle n_e^2 \rangle V$, and the small (starlike) image gave an upper limit on V, so that a lower limit on $\langle n_e^2 \rangle$, and hence an upper limit on the cooling time, could be given. This was done by Johnson (1966) and others, who showed that the cooling time was at most a few years, and shorter than the known history of the optical object, so that a continuing source of energy seemed necessary.

This fitted in well with the notion, first discussed at the Noordwijk symposium (Burbidge, 1967b) but based on an earlier suggestion by Hayakawa and Matsuoka (1964), that the Sco source is a binary system in which gas is escaping from a more extended component and falling into the gravitational potential well of a compact component, which Shklovsky (1967) suggested was a neutron star. Cameron and Mock (1967) put forth a white dwarf instead. They also made the interesting point that the energy release by such infall is self-limited by the pressure of the radiation produced, which, when it balances the gravity, will prevent further matter from falling in. For a central object of 1 $M_{\odot}$ the limit is $\approx 2\times 10^{38}$ erg/sec, which is comfortably above the putative luminosity of the Sco source.

It is easy enough to show that the highest temperature you can get by completely converting the kinetic energy of infall to thermal energy is

$$T_k \sim 10^7\ \mathrm{K}\left(\frac{M}{M_{\odot}}\,\frac{R_{\odot}}{R}\right), \tag{1}$$

where M and R are the mass and radius of the condensed central object. But this is only an upper limit; in the real system it is doubtful that such a high T could be attained. The only real investigation is that by Prendergast and Burbidge (1968), with a computer. They assumed gas to be released from one component with angular momentum typical of a binary orbit. This angular momentum prevents it from falling straight in upon the other component. Instead it forms a swirling disk, and a steady state is reached, with a temperature gradient established in the disk. With $R=1.5\times 10^{10}$ cm $\approx$ $\approx \frac{1}{5}R_{\odot}$ and $M=10^{33}$ gm $\approx \frac{1}{2}M_{\odot}$, the highest temperature they achieved (at the surface of the 'primary' star, where the infall terminates) was only

$$T_{\mathrm{surf}} \sim 10^{-2}T_k, \tag{2}$$

amounting to $\sim 2\times 10^5$ K and clearly not adequate for a source like Sco X-1. The reason why we have (2) instead of (1) is that when the gas reaches the stellar surface it is still rotating. The angular momentum prevents all the kinetic energy from being thermalized. It is possible that the interaction and connection of the swirling gas with the stellar surface would improve the thermalization and raise T, but Prendergast and Burbidge found this aspect of the problem too difficult for adequate treatment.

4. Complications in an Optically Thick System

Of course T can also be raised by taking R smaller, and there is now evidence that R is quite small. Figure 1 is from the recent paper by Neugebauer *et al.* (1969). Their observations of Sco X-1 in the infrared and visible show quite clearly that the source is optically thick there, and even perhaps in the ultraviolet. So instead of just getting a lower limit on n_e, they introduce another relation by assuming that the infrared spectrum is on the Rayleigh-Jeans part of a black body curve at the temperature T indicated by the X-rays. This leads to a source dimension $R \sim 10^9$ cm (roughly the radius of a white dwarf) and to $n_e \sim 10^{16}$ cm^{-3}. It is now possible to check the model for consistency, by calculating optical depths. The optical depth due to free-free re-absorption is only $\tau_{ff} \approx 1.3$ in the infrared and 0.14 in the ultraviolet. This is not really adequate to produce a blackbody spectrum. But the optical depth due to electron scattering *is* quite large in this model, $\tau_{es} \approx 10$–20 depending on the distance D assumed.

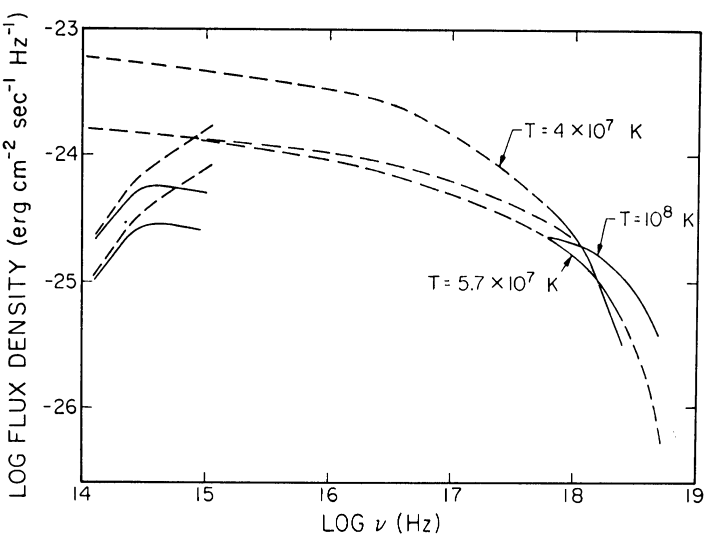

Fig. 1. The spectrum of Sco X-1, from Neugebauer *et al.* (1969). The solid curves near $\log \nu = 18$ are the X-ray fluxes observed at different times. These have been extrapolated (broken curves) to the visible region, assuming free-free radiation by hydrogen at the appropriate temperatures. Between $\log \nu = 14$ and 15 are the infrared and visible fluxes observed at different times (solid curves), and (broken curves) the same fluxes corrected appropriately for interstellar reddening. The failure of these curves to fit the X-ray extrapolations shows that the source is optically thick in the visible.

And, say these authors, the 'true' optical depth is then essentially the harmonic mean, $\tau = \sqrt{(3\tau_{es}\tau_{ff})}$, and is $\gg 1$ in the infrared, justifying the assumption of a blackbody curve. Now I do not think this is quite sufficient; I think that to get the blackbody curve, instead of a graybody, you really need $\tau_{ff} \gg 1$ and not merely $\sqrt{(3\tau_{es}\tau_{ff})} \gg 1$. This needs to be more carefully looked at. But considering the ill-determined distance, unknown geometry, and nonuniform temperature of the source, such a simplifying assumption may not be out of place, and the results do suggest a small source, with $R \sim 10^9$ cm. Chodil *et al.* (1968) got about the same R by just assuming $\sqrt{(3\tau_{es}\tau_{ff})} \sim 1$ in the blue, without the blackbody assumption.

I wish to emphasize that a value for τ_{es} as large as 10–20 will have important effects. A photon produced in this medium will be scattered $\sim \tau_{es}^2 \sim 100$–$400$ times before escaping. If this is a photon with initial energy $h\nu \gg kT$, these are classical Compton scatterings. The mean energy loss per collision by the photon is then

$$\delta(h\nu) \sim \left(\frac{h\nu}{m_e c^2}\right) h\nu; \tag{3}$$

even for $h\nu$ as low as 10 keV this will become important after ~ 50 scatterings, and the effect is clearly to degrade high-energy photons and turn the photon spectrum above $h\nu \sim kT$ into a graybody spectrum at temperature T – which of course is not very different from the bremsstrahlung exponential shape in this energy range anyway. X-ray lines will be smeared too, as already mentioned here by Professor Novick in discussion. Manley and Olbert (1969) called attention to this degradation by Compton scattering, though they seem even to have overstated it by forgetting that with the electrons 'hot' ($kT \sim$ few keV) instead of at rest, the energy loss for the hard photons is self-limiting. Softer photons, of course, are *gaining* energy in the Compton collisions. Here, for $h\nu \ll kT$, the mean energy gain per collision is

$$\frac{\delta(h\nu)}{h\nu} \sim \left\langle \frac{v}{c} \cdot \frac{1}{2}\left(\frac{c+v}{c} - \frac{c-v}{c}\right)\right\rangle \sim \frac{\langle v^2 \rangle}{c^2} \sim \frac{kT}{m_e c^2}, \tag{4}$$

which is $\sim 10^{-2}$, and in 100–400 collisions this too can become important, turning the spectrum into a graybody – which in fact is what the optical spectrum looks like. The good fit to a ν^2 law in the optical band may indicate that we are in a regime where $\tau_{es}^2 kT/(m_e c^2) > 1$ but $\tau_{ff} \ll 1$; then we expect a 'pure graybody'. At lower ν, where $\tau_{ff} \gtrsim 1$, the photon emission is adequate to make the spectrum flatten and move up onto the true blackbody curve.

Of course it is not sufficient to have in this source only one homogeneous region, with a high T. Cooler regions are needed too, to produce the emission lines. We do not know the density in these regions, but it is probably high. If it is similar to that in the X-ray regions, then the volume of cool gas needed is $\sim 10^{-4}$ that of the hot gas (Johnson *et al.*, 1967). This is not much, and it could be just filaments. The requirement is

$$n_{\text{cool}}^{\ 2}\ V_{\text{cool}} \approx 2 \times 10^{54} \left(\frac{D\text{pc}}{100}\right)^2 \tag{5}$$

In models like this we have to be very careful. If the cool gas is imbedded in the hot gas, the optical lines may be smeared beyond recognition by scattering in the cloud of hot electrons; they would in the model of Neugebauer *et al.*, discussed above. On the other hand, if the hot gas is surrounded by the cool gas, the photoelectric absorption of X-rays will become large around 1 keV (which contradicts observations, e.g. Rappaport *et al.*, 1969) if the column depth of cool gas is as large as $nl \sim 10^{22}$ atoms/cm^2. If heavy elements are present in normal abundance, this remains true even if the temperature of the cool gas is high enough to ionize H and He (Bell and Kingston, 1967). From (5), setting $l \sim V^{\frac{1}{3}}$, we can keep $nl < 10^{22}$ if $n_{\text{cool}} \gtrsim 10^{10}$ cm^{-3}. Comparing this with $n_{\text{hot}} \sim 10^{16}$ in the Neugebauer model, we see that the cool

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gas can be spread out quite a bit around the hot source. You will easily recognize that estimates like these are based on a quasispherical geometry; a pancake configuration, as suggested by the binary hypothesis, relaxes such difficulties quite a bit.

Another interesting feature of these high-density models was pointed out by Manley and Olbert (1969). The blackbody temperature corresponding to the X-ray energy density inside the hot cloud of Neugebauer *et al.* is $T \approx 4 \times 10^5$ K! This means that the appearance of the central star, assuming there is one, must be significantly affected by the impinging X-ray flux, since the star must heat its surface up to 4×10^5 K just to shed the energy it acquires from the X-rays. This could explain some of the difficulty in finding conclusive evidence of a binary. It also shows that the optical object must be abnormal in every respect, and that arguments based on analogies with familiar objects are likely to mislead.

Yet another set of constraints on models of this sort is provided by the theoretical and experimental time scales for variations. A few years ago we only knew that the object was small enough to be starlike, and that the cooling time had to be shorter than a year or so. This was already felt to be a possible embarrassment, since the optical object had appeared on plates for 70 years. Now, with R down to 10^9 cm and n up to 10^{16} cm^{-3}, the theoretical cooling time is in the millisecond range. We know there *are* variations in the observable X-ray temperature, but observations are not extensive enough to give a good idea of them. It is pretty clear, however, that the variations in T are not as dramatic as the theoretical cooling time would suggest. There must be a continuing energy source, which may be sporadic, as suggested by the apparent flaring behavior (Lewin *et al.*, 1968a). But then there must also be an analog of capacitance in the system, such as a surrounding reservoir of low-temperature gas, which gradually feeds energy into the hot gas and prevents it from cooling suddenly. The energy source may be variable in time average over a week or a month; then slow variations in T may be explained. This is only speculation, and no one seems to have looked very carefully at the problem. It appears that such behavior might be achievable in a model of the Prendergast-Burbidge type.

Simultaneous optical and X-ray observations have not been numerous. What data there are (Chodil *et al.*, 1968) suggest that the optical continuum is brightest when the X-ray temperature is *lowest*. This is the reverse of what you would expect from a straightforward interpretation of the high-density model. I do not want to spend more time on this, so I shall just refer you to the discussion in the paper cited.

5. Iron Lines

Tucker (1967) pointed out that there is a sensible way to test a thermal model when high spectral resolution is available in the X-ray band: namely, to look for characteristic X-ray emission lines of heavy elements, particularly the lines of H-like and He-like iron ions near 7 keV. Holt *et al.* (1968) tried this on observations of the Crab to see if they could already eliminate Sartori and Morrison's (1967) thermal model for that object, and even found that they could, at least for certain choices of element abundance. However, it seems that this test is not so easy. The NRL group (Fritz *et al.*, 1969) had observations of even higher resolution on Sco X-1, which we think *is* thermal, and they could not see any iron lines either! Further improvements in spectral resolution are needed, and obviously we will not have faith in this test of models until we demonstrate that the lines *can* be seen in at least one thermal object. I think also that there is some inconsistency between the calculations performed by the NASA group and by the NRL group*, and between them and the work of Wally Tucker on which they both relied. Wally is the *eminence grise* of this subject, but unfortunately he is not here to give us an opinion. I do not like to take sides in a struggle between two arms of the U.S. government, but it appears to me that the analysis of Holt *et al.* is more nearly correct. Possibly there are also some misprints in the Tucker paper. This all needs reworking.

6. Sco X-1 as a Radio Source

It is necessary to say something about the radio observations of Sco X-1 (Ables, 1969). It is a weak but detectable source at 6 cm, and varies by roughly a factor of 10 in a few hours; the average strength is $\approx 3 \times 10^{-28}$ w m^{-2} Hz^{-1}. This is well *below* the extrapolation of the optically thin X-ray bremsstrahlung spectrum to radio wavelengths. But now we know that the bremsstrahlung spectrum already becomes optically thick in the visible, and so the radio flux now represents an *excess*. There is also a weak positive radio result on Cyg X-2 (Moffet and Berge, 1968)**; it lies about a factor of 10 *above* the bremsstrahlung extrapolation. But this may be a similar story. There are many ways of explaining an excess. We could have some large region at low T producing thermal radiation at the longer wavelengths, or we could have some nonthermal process occurring, such as synchrotron radiation. Riegler and Ramaty (1969) and Feldman and Silk (1970) both have proposed this. I have not studied these proposals hard enough to understand them very well, but it seems clear that, with observations at only one radio frequency and no spectral information, there is a good deal of elbow room for theorists. In both of these models the fields contemplated are rather strong, 1–100 gauss, but this may be appropriate for a circumstellar region. The radio phenomenon may be something like a solar flare. Feldman and Silk suggest that nonthermal electrons in a power-law spectrum produce the radio emission, and also, through nonthermal bremsstrahlung, the variable X-ray tail at $h\nu > 30$ keV. This would be much like what we see on the sun (Holt and Ramaty, 1969).

7. Other Models

I am coming to the end of what I, as a novice, can say about the theories of sources of the Sco X-1 type. The most elaborate work has been done by Prendergast and

* *Inter alia*, the 'correction' proposed by the NRL group to the earlier NASA paper appears to be in error.

** Note added June 30, 1969: Apparently this result was spurious (Purton and Andrew, 1969).

Burbidge, but it does not begin to cover the complexities of the problem. It seems to me that no dramatic new theoretical ideas are in the offing, and that we simply have on our hands a rather dirty problem in 'applied maths'. I should mention a modification of the binary idea, proposed by Cameron (1969); he suggests that a single star has formed a kind of planetary nebula *manque*; it gave the planetary shell too little energy to escape, so it stopped expanding, and now dribbles slowly back onto the star, producing the X-rays. This model, of course, is even less worked out than the other.

Little has been said here about the contrasting theory of Sco X-1 due to Manley and Olbert (1969), and I might be accused of neglecting it. Indeed this is a ponderous preprint they have sent out, and I have to confess that I have not studied it carefully enough to say anything very intelligent. The model involves a pre-stellar cloud, containing gas at $\approx 10^5$ K which produces the emission lines, and also hydromagnetic turbulence which accelerates electrons by a Fermi-type process, forming a power-law electron spectrum with a high-energy cutoff. The synchrotron emission can then match the observed X-ray spectrum pretty well. There are two adjustable parameters describing the turbulence, plus the customary n and T for the gas. A possible objection to this theory is that there does not seem to be any place in it for a *star*, so that we cannot apply it to Cyg X-2, where sharp stellar absorption lines are seen.

At La Jolla I shared an office with Wayne Stein, who sat there poring over his observations of infrared stars, trying to make some sense of them. One day I glanced at his notes and saw that he had scribbled in the margin, 'What is this little star saying? What is he trying to tell us?' Since then I like to think of the X-ray data in the same terms. It seems to me that Sco X-1 and Cyg X-2 are trying as hard as they can to 'tell us' (a) that they are essentially thermal objects, and (b) that the energy is coming from gas streams and/or binary motion. A complicated theory like that of Manley and Olbert which starts off in a different direction, when the need for such a departure has not been demonstrated, may be ingenious, but it has a low a priori probability of being right.

8. Absorption in the Sco X-1 Spectrum

Now I want to introduce one final topic related to Sco X-1, namely the question of its distance, and the interstellar absorption in its direction. I have left this until last because it may have more intrinsically to do with theories of the interstellar medium than with theories of X-ray sources; nevertheless I should discuss it, if only because I know rather more about it than about some of the source theories. There are now two contradictory determinations by optical astronomers of the distance to Sco X-1. Sofia *et al.* (1969) have measured a proper motion and identified Sco X-1 as a member of a subgroup within the Scorpio-Centaurus association. This puts it at $D = 170$–200 pc. Wallerstein (1967), and later Westphal *et al.* (1968), measured the interstellar H and K absorption lines of Ca^+ and found them stronger than in any nearby stars (in particular, stronger than in any stars of the Sco-Cen association); they concluded $D > 300$ pc. Whichever D is correct, it is large enough to pose difficulties with the

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observed *lack* of X-ray absorption. Sco X-1 has galactic latitude $b^{\mathrm{II}} \approx 24°$, so that by the time we reach $D = 170$ pc we are 70 pc above the galactic plane. Thus almost half the total column density of atomic hydrogen in this direction should lie between us and Sco X-1, or *more* if $D > 170$ pc. How much hydrogen is there in this direction? I have not been able to find a high-resolution 21-cm radio map for this part of the sky, but on a 5° grid with 2° resolution (McGee *et al.*, 1966) the closest points give

$$N_{\mathrm{H}}^{(\infty)} \equiv \int_0^\infty n_{\mathrm{H}}\, dl \approx 1.8 \times 10^{21} \text{ atoms/cm}^2, \tag{6}$$

and the variation seems rather smooth.

With what should we compare this? There is an X-ray measurement at 0.25 keV by the NRL group (Fritz *et al.*, 1968). The flux reported has decreased by a factor of 6 from a previous measurement by the same group, and so we might have a little residual skepticism about the latest result. But for sake of argument let us accept it. It lies quite nicely on the bremsstrahlung curve extrapolated from higher X-ray energies and is therefore consistent with *zero* photoelectric absorption at 0.25 keV; apparently $\tau = 0.5$ is an upper limit for the optical depth. The absorption at this energy is due mainly to H and He, and if we know the abundance ratio we can use the theoretical cross sections (Bell and Kingston, 1967) to derive from the X-ray result an upper limit to $N_{\mathrm{H}}^{(D)} \equiv \int_0^D n_{\mathrm{H}} dl$ out to Sco X-1. Table I shows some results, for several assumed values of the ratio $n_{\mathrm{H}} : n_{\mathrm{He}}$. Note particularly the last column. If we reject the NRL datum, we must fall back upon measurements by the MIT and Livermore groups (Rappaport *et al.*, 1969; Hill *et al.*, 1968) at 0.6 keV, which indicate $\tau < 0.5$ at this energy, and the last column gives the corresponding limits.*

We must compare these numbers, particularly the NRL numbers, with $N_{\mathrm{H}}^{(\infty)}$ in (6). You can see that the result is rather sensitive to the unknown helium abundance. Case (a) might possibly be consistent with (6), but a zero abundance of He in interstellar matter cannot seriously be entertained. Case (c) is for the 'cosmic abundances' of Aller (1961) and gives the biggest discrepancy; in any case there is some observational evidence, summarized by Biermann (1969), for an He abundance lower than this in interstellar matter. Case (b) is for 25% He by mass, as produced by a big bang without any further processing of elements, and it seems that we must assume at least this much He; also it corresponds to the smallest observational estimate for interstellar matter. So we have to explain the discrepancy with (6).

It is possible that there is a little 'hole' in the direction of Sco X-1, so that the amount of H out to 170 pc, or even out to infinity, is smaller than we think. A high-resolution 21-cm map would clarify this. But other evidence suggests that the phenomenon is more general. Observations of the Lyman-α absorption line in spectra of nearby stars

* These numbers are a little larger than those derived by Rappaport *et al.* This is mainly because I have included only absorption by H and He. 0.6 keV is above the K-edges of C, N and O, and if these elements are present the numbers in the last column have to be decreased by a factor which can be as large as 2 or 3.

(Jenkins and Morton, 1967) have also indicated less H than would be expected from the 21-cm observations. Kerr (1969), in a review, has discussed the idea that the sun is in a local region of low gas density, perhaps 200 pc in radius. The 21-cm observations give no information about regions so close, and the H seen in 21-cm radiation could all be farther away. More observations will be needed to test this notion, and X-rays may play a significant part.

TABLE I

Some limits, derived from X-ray measurements, on the column density of hydrogen out to Sco X-1

		$N_H^{(D)} \equiv \int_0^D n_H\, dl$	
	$n_H : n_{He}$	NRL (0.25 keV)	MIT (0.6 keV)
(a)	$\infty : 1$	$< 5 \times 10^{20}$ cm^{-2}	$< 7 \times 10^{21}$
(b)	$12 : 1$	$< 1.4 \times 10^{20}$	$< 2.3 \times 10^{21}$
(c)	$6 : 1$	$< 8 \times 10^{19}$	$< 1.4 \times 10^{21}$

A small value of $N_H^{(D)}$ will solve the problem of Table I, but it will not explain the *strength* of the Ca^+ lines in the optical spectrum. Westphal *et al.* (1968) assert that there is no star within 300 pc having such strong Ca^+ lines. From these lines they derive by a classical method

$$\int_0^D n_H^2\, dl \approx 2.7 \times 10^{20}\ \text{cm}^{-5}. \tag{7}$$

From this and $N_H^{(D)} < 1.4 \times 10^{20}$ we have

$$[n_H] \equiv \frac{\int_0^D n_H^2\, dl}{\int_0^D n_H\, dl} > 2\ \text{cm}^{-3}, \tag{8}$$

which is not unreasonably high if the medium is cloudy. The 'classical method', however, is known generally to give incorrect results. There is a well-known calcium discrepancy, which goes in the wrong way for us and is probably connected with the tendency of the interstellar calcium to get locked up in grains. The effect is counteracted to some extent by extra ionization due to low-energy cosmic rays, but typically (G. B. Field, private communication; I cannot take time to go into more detail here) the number (8) would become $2 \times 40 = 80$ instead of 2, and this is a pretty extreme requirement for the interstellar clouds. Perhaps the lines originate instead in a local abnormal region near Sco X-1. This possibility was discounted by Wallerstein (1967) and by Westphal *et al.* (1968) because the velocity of the K-line is only 7 km/sec, perfectly typical of an interstellar cloud. Still, this whole question clearly needs re-examination.

Of course the easiest ways out of these difficulties involve disbelieving the X-ray data and/or their interpretation. If we merely reject the NRL result (i.e. switch from column 2 to column 3 in Table I) it appears that no real inconsistencies would remain, except that in case (c) we might have some difficulty with strong X-ray absorption by C, N, and O. Alternatively, we might just assume that the intrinsic spectrum of Sco X-1 from 1 to 0.25 keV has an additional, steeply rising, low-temperature component, not observed at higher energies. This then allows the observed flux at 0.25 keV to reflect a fair amount of absorption. It is not clear how much of this low-temperature (10^6–10^7 K) flux could be allowed without betraying itself in the 0.6 keV measurements. Spectral data in the soft band should clear this up quite soon.

X-ray absorption is a valuable tool for learning about the interstellar medium. A soft X-ray observation of the Crab would be especially valuable; an attempt was made by the Livermore group (Grader *et al.*, 1969), but there were atmospheric background problems. Absorption has been seen at a few keV for two sources in Sagittarius, presumably buried deep in the gas of the disk (Gorenstein *et al.*, 1967; Rappaport *et al.*, 1969). The K-lines of interstellar O and Ne at 0.53 and 0.87 keV should particularly be looked for (Felten and Gould, 1966; Bell and Kingston, 1967), and the degree of energy resolution already achieved (Hill *et al.*, 1968) is not far from that required to show them.

9. Other Galactic Sources

This is all I want to say about the Sco X-1 and Cyg X-2 type sources. Centaurus X-2, identified as the star WX Cen by Eggen *et al.* (1968), seems to belong to the same category. It is known to be a variable X-ray source, possibly of thermal character (Harries *et al.*, 1967), but it has a nonthermal tail at high energies, like Sco X-1 (Lewin *et al.*, 1968b). As for the unidentified galactic sources, many of the X-ray spectra are ill-known and still amenable to either a thermal or a power-law interpretation. It has long been known, though, that the Sagittarius sources as a group are distinctly harder than Sco X-1 (Giacconi *et al.*, 1965), and lately we see that the individual spectra of Cyg X-1, Cyg X-3, Cyg X-4, Lup X-1, GX 3+1, and GX 354−5 all seem to prefer a power-law fit (Peterson *et al.*, 1968; Buselli *et al.*, 1968; Hudson *et al.*, 1969; Rocchia *et al.*, 1969). This tempts me, for one, to the hypothesis that most of the unidentified sources are supernova remnants, like the Crab, or related objects in the disk population. Dr. Gratton has included in his review the very diagram I wished to show, comparing the distribution of X-ray sources in galactic coordinates with that of known novae. Curiously, I would have drawn conclusions different from his. I would have suggested that the mean latitude of X-ray sources is significantly smaller than that of novae, and that the former are true spiral-arm Population I objects rather than intermediate objects like the latter. This was also the point of view of Gursky *et al.* (1967), and I will refer you to the attractive figures in their paper rather than reproducing them here. If the Sagittarius and Cygnus sources are in the spiral arms, at distances of several kpc, then their absolute luminosities are comparable to the Crab. But if the Sagittarius sources are clustered around the galactic center, like novae, then they must be much brighter than Sco X-1. This, it seems to me, suggests the former as prototype rather than the latter. I should also refer you to the coincidences between supernova remnants and X-ray sources found by Poveda and Woltjer (1968). But this question must be settled by observation, and I should not waste more of your time speculating on it.

10. γ-Ray Sources

This seems the moment to say something about γ-ray sources. No point sources have been established, though there is continuing suspicion, with observations at the limit of sensitivity, that the Crab and possibly the pulsar CP 1133 are sources at 10^{11}–10^{13} eV (Fegan *et al.*, 1968; O'Mongain *et al.*, 1968; Charman *et al.*, 1968). Throughout the γ-ray band the sensitivities of observations need to be increased before much can be expected. Observations with poor angular resolution near 100 MeV have, however, shown quite clearly that there is a band of emission along the galactic plane (Clark *et al.*, 1968). It is possible to interpret this as π-γ secondaries from cosmic rays colliding with gas in the galactic plane, but the intensity is 20–50 times higher than would have been expected. Raising the cosmic-ray density or gas density in the inner parts of the Galaxy causes a variety of more or less severe difficulties for cosmic-ray theory; the matter is too complicated to discuss at length here. Alternatively, the intense far-infrared radiation reported by Shivanandan *et al.* (1968), if real, may permeate the galactic disk, and then Compton scattering on cosmic-ray electrons can give the γ-ray flux. This point of view has been argued by Cowsik and Pal (1969) and by Shen (1969).

There is a third explanation, however, which seems reasonable and has been discussed by Ogelman (1969): The γ-ray flux may be merely the unresolved sum of the galactic X-ray sources, extrapolated to the 100-MeV band. If most of the unidentified X-ray sources have power-law spectra $n(\nu)\, d\nu \propto \nu^{-2} d\nu$, as observed for the Crab, Cyg X-1, and the Sagittarius sources as a group, then the numbers work out about right. Indeed there is even a peak at the location of the Crab in the data of Clark *et al.*, and it may be that this represents a real observation of the Crab as a γ-ray source. Eliding details, if we have synchrotron X-rays from these objects, it does not transgress the bounds of the possible to have synchrotron γ-rays as well. If these supernova remnants are the sources of galactic cosmic rays, making this hypothesis is really equivalent to saying that the γ-rays are the tail of the synchrotron radio spectrum of cosmic-ray electrons in the Galaxy! This possibility was mentioned by Verma (1968) and much earlier by Friedlander (*c.* 1962). (At this early date, synchrotron γ-radiation was thought preposterous, so Friedlander suffered heavy criticism and withdrew the idea.) Of course at these high frequencies the emission must all occur near the cosmic-

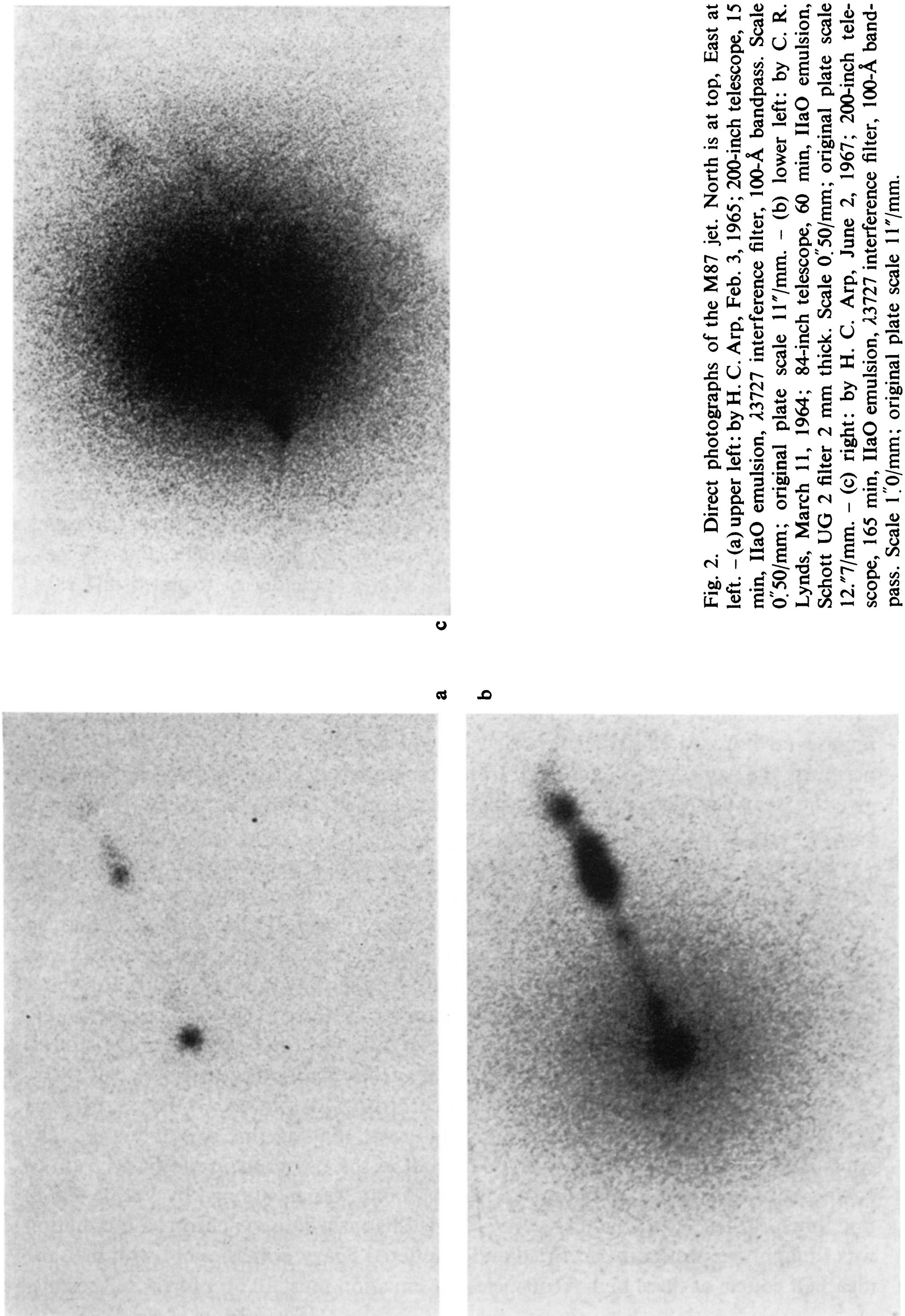

Fig. 2. Direct photographs of the M87 jet. North is at top, East at left. – (a) upper left: by H. C. Arp, Feb. 3, 1965; 200-inch telescope, 15 min, IIaO emulsion, λ3727 interference filter, 100-Å bandpass. Scale 0.″50/mm; original plate scale 11″/mm. – (b) lower left: by C. R. Lynds, March 11, 1964; 84-inch telescope, 60 min, IIaO emulsion, Schott UG 2 filter 2 mm thick. Scale 0.″50/mm; original plate scale 12.″7/mm. – (c) right: by H. C. Arp, June 2, 1967; 200-inch telescope, 165 min, IIaO emulsion, λ3727 interference filter, 100-Å bandpass. Scale 1.″0/mm; original plate scale 11″/mm.

ray sources (rather than diffusely throughout the Galaxy as at radio wavelengths) – but this is precisely Ogelman's suggestion.

11. Extragalactic Sources; M87

Among extragalactic objects one certainly expects the Magellanic Clouds to be sources, but reports at this conference leave us in doubt whether they have been detected. If the reported measurement of the Large Magellanic Cloud by the Livermore group (Mark *et al.*, 1969) *is* correct, the flux is just about what one would expect if the Cloud contains sources similar to those known in the Galaxy.

There is a weak high-latitude source in Leo, but I have heard nothing more of this since the first report by the NRL group (Byram *et al.*, 1966). I believe three other high-latitude sources have been announced at this conference. Of course any of these may well be extragalactic, but we need identifications.

This leaves us with M87 (Byram *et al.*, 1966; Friedman and Byram, 1967; Bradt *et al.*, 1967; Haymes *et al.*, 1968). The position of the X-ray source is still, I think, known only to a few degrees accuracy in right ascension, but in declination it coincides with the galaxy to within 0.1°, and at its high latitude the identification seems sure. Figures 2a, b, c (Felten *et al.*, 1970) show several recent photographs of the famous jet in this galaxy. Figures 2a and 2c are taken through an [O II] λ3727 interference filter, but the jet radiation is probably continuum coming through the filter. (In Figure 2c, however, which is printed at half-scale to show the outer parts of the galaxy, the counter-jets (Arp, 1967) can be seen, and these apparently *are* line radiation.) The distance* from the nucleus of the galaxy to the tip of the jet is at least 1500 pc (depending on projection angle), and a filamentary extension can be seen. The bright part of the jet is at least 400 pc long, but it is a matter of dispute whether the bright condensations within it are resolved (de Vaucouleurs *et al.*, 1968; Felten *et al.*, 1970); their diameters are certainly $\leqslant$70 pc. The bluish continuum of these knots is strongly polarized, making it quite certain that we are seeing optical synchrotron radiation.

Now there is also a strong radio source in the central region of this galaxy. Figure 3 is a radio map from the Cambridge interferometer (Macdonald *et al.*, 1968). The source is some 50″ long East-West, longer than the optical jet, and overlaps to the opposite side of the galactic nucleus, though it seems to be aligned parallel to the jet. Other observations (Lequeux, 1962) suggest that there are two peaks at the ends of this area. The source has not been resolved perpendicular to the jet. It is known, however, that finer structure is present; a few percent of the flux arises in hot spots $<0\overset{''}{.}01$ in diameter. Clearly this radio source is related to the optical jet but not identical in form; the exact relation is debatable.

Figure 4 (after Felten, 1968) collects flux densities for this object over a wide frequency range. The radio 'halo' spectrum is subtracted away to yield that shown for the 'core' source. A power-law extrapolation $\nu^{-0.75}$ is shown, but we see that the

* Distances here are based on $1'' = 72$ pc, for $D = 14.8$ Mpc, given recently by Sandage (1968).

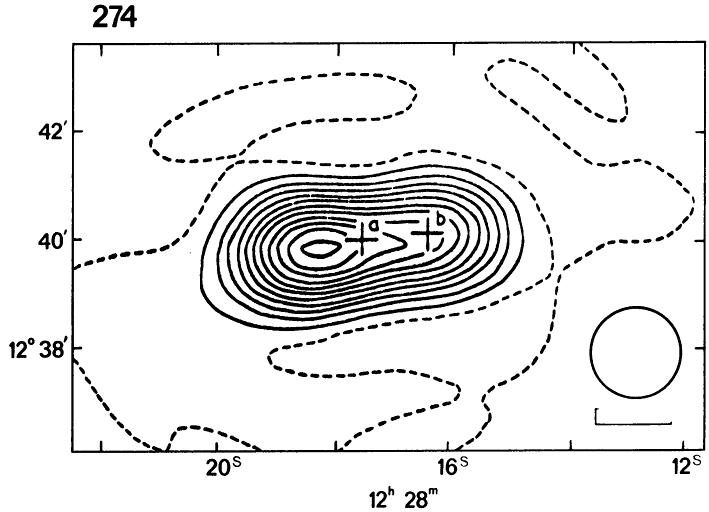

Fig. 3. A radio map of the core source in M87 at 1407 MHz (Macdonald *et al.*, 1968). 'a' is the position of the galaxy nucleus and 'b' the tip of the optical jet. The vertical scale is compressed, for coordinates have been chosen to make the beam shape circular; the unequal orthogonal arms show the length of 20″ of arc in each coordinate. Beam size is shown. The source is unresolved perpendicular to the jet axis.

evidence for this is by no means conclusive. Though the scatter in optical measurements of the jet is large, recent optical and infrared results suggest a possible falloff in the optical band. In soft (1–10 keV) X-rays, there is now a considerable discrepancy between the Leicester results reported here (Adams *et al.*, 1969) and the earlier NRL and MIT measurements ('F' and 'Br' in Figure 4). Above 10 keV we have only a rash of upper limits, and one positive result (Haymes *et al.*, 1968), which is now much in doubt because, as shown, it conflicts with a 2σ upper limit from McClintock *et al.* (1969). Lacking positive observations in the hard band*, we are free to draw in almost any kind of fit to the soft X-ray data; a thermal bremsstrahlung curve at $T=10^8$ K is shown as an example (Sartori and Morrison, 1967).

Nevertheless we know that the optical flux *is* synchrotron radiation. Regardless of the X-ray situation, the optical radiation poses big problems in a system as large as this. Suppose the fast electrons are injected at the nucleus. If equipartition prevails in the jet (and this assumption leads to $B \approx 3 \times 10^{-4}$ gauss), then the lifetimes of the electrons radiating at optical frequencies are only ≈ 100 yr. They cannot reach the distant outer parts of the jet! If B is weaker than the equipartition value, the lifetimes become longer, but still the electrons have to stream outward along the jet in order to make it, and the hose instability would then be expected to 'break off' the outer jet from the particle source at the nucleus (Felten, 1968). Another possibility is that the

* The published upper limit at 50 MeV (Frye and Wang, 1968) is a factor of 5 below the power-law extrapolation. Greisen (1968) has an unpublished measurement at 1 GeV which is said to lie on the extrapolation, but the statistics are poor.

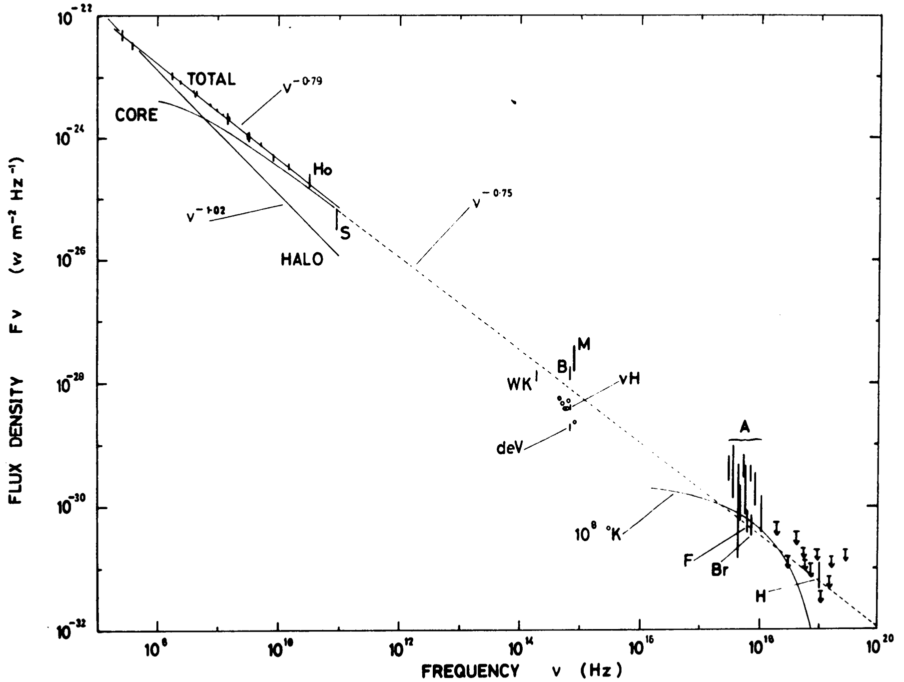

Fig. 4. The electromagnetic spectrum of the M87 jet. References to many of the data may be found in the paper by Felten (1968). Recent results include: Ho: Hobbs *et al.* (1968). S: Schorn *et al.* (1968). WK: Wisniewski and Kleinmann (1968). Open circles: Pronik *et al.* (1967). deV: de Vaucouleurs *et al.* (1968). A: Adams *et al.* (1969). The upper limits shown above 10^{18} Hz are at 2σ and are due to Hudson *et al.* (1969), Overbeck and Tananbaum (1968), and McClintock *et al.* (1969). The positive result 'H' is that of Haymes *et al.* (1968). The power-law extrapolation shown has equation $F_\nu = 10.6 \times 10^{-18} \nu^{-0.75}$. A sample thermal bremsstrahlung curve at 10^8K is also drawn through the X-ray measurements.

ambient plasma is also moving outward, carrying the fast particles and field within it. In this case there need not be any streaming of fast particles relative to field – or if there is, and the field as a result becomes unstable and jumbled, the moving cloud still carries fast particles and field along. Therefore in this model we can make B quite small, and the synchrotron lifetimes long. But an upper limit on the lifetime of an optical electron is always set by Compton loss to the high-density optical and infrared photons (the Compton-synchrotron process), and the lifetime this allows the optical electrons is only about 2×10^4 yr.* If the optical electrons are to survive the journey of >5000 light years from the nucleus, then, the plasma cloud must move at $v \gtrsim 0.2c$. This is possible, though perhaps not very likely. Such a model can be tested better

* Anyway, Rieke and Weekes (1969) have recently pointed out that the field in the jet cannot be arbitrarily weak; as we decrease it, the required flux of fast electrons goes up, and eventually the Compton-synchrotron γ-rays at $\sim 10^{13}$ eV produced by these electrons would exceed observational limits. This happens for $B \sim 10^{-5}$ gauss, a value which again gives a maximum lifetime $\sim 2 \times 10^4$ yr for optical electrons in the jet.

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when we have knowledge of the spectrum and, particularly, the spatial distribution of the X-ray source.

Time-scale difficulties of this sort can be overcome if one is free to postulate large inhomogeneities in the field. Then a fast electron can enjoy a period of 'rest' in a weak field, move briefly into a small volume of strong field where it can radiate optical or even X-ray photons, and then 'rest' again (Apparao, 1967). It is difficult, however, to maintain such inhomogeneities. A shock wave, e.g., will not usually propagate a field ratio greater than about 4:1, but we need a ratio more like 100:1 if it is to be of much use. Burbidge and Hoyle (1969) have suggested that the Crab contains massive condensed objects, which can retain strong fields at their surfaces, and Burbidge (1967a) proposed that condensed bodies of 10^6–$10^8 M_\odot$ were actually ejected from the nuclei of galaxies to form objects like the M87 jet. Such massive bodies could of course be injecting the cosmic rays as well as providing the strong fields in which they radiate.

Another model for the M87 jet, suggested when the time-scale problem first became apparent (Burbidge, 1956), is the 'secondary-production' model, in which a large reservoir of cosmic-ray primaries is injected initially, and later provides continuing injection of fast electrons throughout the confinement volume by pion production in collisions with ambient gas nuclei, followed by π-μ-e decay. I have recently investigated several variants of this (Felten, 1968; Felten *et al.*, 1970). The fundamental difficulty which arises is the large cosmic-ray pressure introduced by the primaries, equivalent to that exerted by a field of $\sim 10^{-2}$ gauss. It is not likely that this can be balanced by a general field in the galaxy or by any other external agency. If the cosmic rays are confined to the volume of the optical jet, the energy content is $\sim 10^{56}$ erg, and an ambient gas density $n \sim 400$ cm^{-3} is needed within the jet to maintain it against the internal pressure for $\sim 10^5$ yr. It is possible to imagine conditions under which this large mass of gas ($3 \times 10^7 M_\odot$) would not yet have been detected spectroscopically, but it is not easy. If, on the other hand, the cosmic rays occupy a much larger volume (as suggested by the size of the core radio cloud), and the optical knots are visible simply because they are regions of dense gas where the p-p collisions occur, then the gas density required is somewhat lower, but of course the total energy involved in the cosmic-ray primaries becomes much larger. In none of these models is a time-scale much greater than 10^5 yr feasible. For fuıther details, see the papers cited.

Of course we can always suppose that these optical electrons are being obtained through some continuous hydromagnetic acceleration process occurring in the outer part of the jet. I should mention, e.g., the 'galactic flare' model of Sturrock (1969, 1967), shown in Figure 5. The primeval intergalactic field, having been gathered in at the waist in the collapse of the protogalaxy, is amplified in the finished galaxy and forms a neutral sheet all around the equatorial plane. Tearing-mode instabilities can then cause field annihilation at any point in this neutral sheet. Sturrock's rough calculations indicate that electric fields of a few volts/meter can result and can accelerate particles to energies of 10^{18} eV. The observed luminosity of the jet can be supplied if the amplified field in the galaxy is as high as 10^{-3} gauss, and Sturrock finds this value appropriate to his model of galaxy formation if $M_{\rm gal} \gtrsim 10^{10} M_\odot$. It should be noted that Sturrock's calculations assume essentially 100% efficiency for acceleration of fast particles in the field-annihilation process. Surely the true efficiency depends on the gas density, and one would think that most of the field energy would go into heat. The idea deserves a more careful investigation.

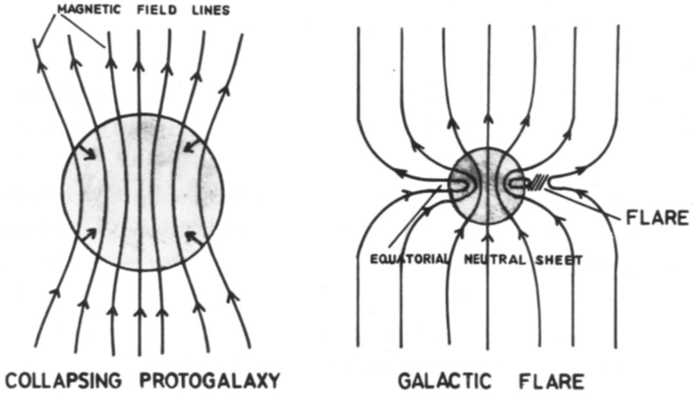

Fig. 5. Sturrock's (1969) model of the M87 jet as a 'galactic flare'. An unstable neutral sheet is formed in the equatorial plane of the galaxy by the primeval field trapped in the gravitational collapse of the protogalaxy. At any subsequent time, the tearing-mode instability may initiate field annihilation and reconnection anywhere on this neutral sheet.

I hope I have not bored you with this recital of theoretical possibilities. Perhaps it can fairly be said that all the models of M87 which are at all successful at the moment are faintly cranky – which only shows that here we are venturing into the unsolved problems of energy supply in extragalactic astrophysics. Let me mention that Haymes *et al.* (1969) have looked for X-rays above 34 keV from Centaurus A and not found any, which means that the X-ray flux from this object, if any, must lie well below the extrapolation of the power-law radio spectrum. This is not surprising, since we do not know of any optical synchrotron radiation from Cen A. For the moment M87 seems unique.

12. Other Processes

The processes of thermal bremsstrahlung and synchrotron emission, with which this review has been almost entirely concerned, have the advantage of high efficiency; that is, once you have your energy in hot gas or in fast electrons respectively, a good fraction of it tends to be given up through the specified process. Other mechanisms of X-ray production which theorists have suggested, but which are not known to be important in any of the discrete sources, are generally *inefficient* in competition with other loss processes acting. I shall discuss some of these briefly.

(a) *Compton (='inverse Compton') loss.* This depends on the ambient radiation density, which is quite low, at least by comparison with other processes acting in discrete sources. Its efficiency can, however, reach appreciable values under certain circumstances:

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(i) In sources with high densities of synchrotron radiation, Compton scattering of the synchrotron photons on the fast electrons may occur (the Compton-synchrotron process). Gould (1965) pointed out that for the Crab, the expected flux of scattered photons around 10^{13} eV (where high-sensitivity detectors have most easily been achieved) was not far below the observational limit. This flux may have been observed by now, or may be shortly (Rieke and Weekes, 1969). Note also the relevance of this process to M87, discussed earlier.

(ii) In the intergalactic medium all other relevant densities are probably low, and Compton loss to the primeval blackbody photons becomes the dominant process for fast electrons, if any are present.

(iii) In discrete sources at an early epoch ($z \gg 1$) the blackbody radiation density is large, being $\propto (1+z)^4$, and the Compton process can again be dominant (Felten and Rees, 1969). Cases (ii) and (iii) are of great interest in theories of the diffuse background, but I will not discuss them further here.

(b) *π-γ γ-rays from cosmic rays.* The galactic cosmic rays probably make enough of these to be observable as a flux (peaked near 60 MeV) in the galactic plane before too long. The process is not likely to be important in discrete sources, but its occurrence does put some limits on models of these sources; e.g., in a secondary-production model of the M87 jet, the failure to observe π-γ photons around 10^{13} eV implies that $B < 7 \times 10^{-5}$ gauss (Felten, 1968).

(c) *Nonthermal bremsstrahlung, by either protons or electrons*, is inefficient, in that only $\sim 10^{-4}$ of the energy loss goes into photons; the bulk goes instead into ionization loss (or elastic Coulomb collisions if the ambient gas is ionized). Therefore these processes are rather extravagant in the particle energy required to explain a given photon flux. Again, however, they seem to be of interest in dealing with knotty problems of the diffuse background spectrum. Hayakawa (this conference), Silk and McCray (1969), and Boldt and Serlemitsos (1969) have all discussed models of this type. The strong heating of the gas implied by the required fluxes of fast particles should never be forgotten in these calculations.

(d) *Proton synchrotron radiation* has been considered by Rees (1968). It can hardly be important except in regions of very strong field, $B \gtrsim 100$ gauss.

13. Conclusion

Let me close this review by confirming what some of you may have gathered from my skeptical, even sardonic, tone: I have become something of a theoretical philistine in recent years. Big ideas do not thrill me much any more, because there are too many people having these big ideas, combining one particle flux with another like the ingredients of a cake, and not enough who are careful to check out the full consequences of their ideas. Also there is too much rationalizing and too little predicting – and in saying this I realize that my own papers are as vulnerable as anybody else's. Here in Rome, in a market square called Campo dei Fiori, a simple monument and eloquent inscription, set up after Rome was freed from the Vatican in the 19th century, mark the spot where Giordano Bruno was burned in 1600. Franco Pacini pointed out to me that Bruno was in fact burned for his heretical cosmological ideas, and suggested that if this punishment were reinstated, the present flood of astrophysical speculation would be much reduced! Well, no one is going to go that far, and if I am being too gloomy in these remarks, forgive me, and wait until the next symposium, when I am sure that the reviewer will take a more cheerful line.

Acknowledgements

I wish to thank Bob Gould, who passed on to me the opportunity to give this talk. Many colleagues gave me advice, and I should name especially George Field, Martin Rees, and Joe Silk, for without their help my amateur's task of digesting this material would have been even more painful than it was. I have also benefited from Geoffrey Burbidge's recent review (November 1968).

(Because of time pressure, parts of this paper had to be omitted in the oral presentation.)

Note added in proof (February 11, 1970): In this rapidly developing field it seems necessary to mention several recent papers pertinent to matters discussed above. Monte Carlo calculations for the broadening of X-ray lines by Thomson scattering in a thermal plasma have been presented by Angel (1969). There is evidence that iron lines are in fact present in the X-ray spectrum of Sco X-1 (Holt *et al.*, 1969).

Absorption of soft X-rays has been detected in the Crab spectrum, and also in Sco X-1 (Grader *et al.*, 1970). In the latter the absorption is apparently time-variable, which suggests that it is mainly circumstellar; then the optical Ca^+ lines are not indicators of the distance, which must be regarded as highly uncertain. Perhaps the value suggested by proper motions, $D \approx 200$ pc, is the best guess.

A discrete γ-ray source in Sagittarius is reported (Frye *et al.*, 1969). The diffuse γ-ray flux in the galactic plane may need some revision.

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