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EXTRAGALACTIC ASTRONOMY

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I. INTRODUCTION

Most of the observational data and theoretical studies of cosmic rays concern processes at work in the Galaxy--solar activity and solar system interactions, particles produced and/or accelerated in active stellar systems and the interstellar medium, and particles ejected by nova and supernova explosions, or accelerated in the shock waves of supernova shells.

In discussing the relevance of extragalactic astronomy to cosmic ray physics, it is therefore necessary to consider what extragalactic objects exhibit physical processes of the same kind as those thought to be important within the Galaxy. In this paper, therefore, I shall describe some components of the active extragalactic universe where comparisons may be drawn with galactic cosmic ray sources.

For cosmic rays to be produced, there needs to be a source of high-energy particles (either baryons or leptons), magnetic fields which can interact with the particles, and, concomitantly, high-energy photons.

The obvious feature of galactic objects that may be sources of cosmic rays is that they must have a mechanism for ejecting high-energy particles. Since supernovae and supernova remnants, where ejection is known to occur, are seen as sources of synchrotron radiation, i.e. they produce high-energy particles in the presence of a magnetic field, we need to look at extragalactic sources of synchrotron radiation, that is, radio galaxies and quasars. Since these sometimes exhibit bulk relativistic motion, it is interesting to make a comparison between what we can only see at low resolution in extragalactic objects, because of the large distances involved, and what maybe analogous processes seen relatively nearby, where a detailed model can be constructed.

The X-ray binary star SS433 is very interesting in this respect. This system consists of a primary component orbiting about a collapsed component; infall of matter into the gravitational potential well of the latter produces sufficient heating for X-ray emission, and, most remarkable of all, the collapsed component must be rotating, have a strong magnetic field, and have an axis inclined to the axis of the orbital plane of the binary. By little-understood mechanisms, bulk matter is accelerated outward and ejected in two opposite, precessing, highly collimated beams, at the near-relativistic velocity of $\sim c/3$. The binary is surrounded by a radio source presumably originating from particles accelerated by the inner activity.

Collimated beams of relativistic electrons are the hallmark of radio galaxies and quasars, and jets are common features in these and in Seyfert galaxies, so in this paper we will discuss some recent data on radio galaxies, active galactic nuclei (AGNs), and quasars (QSOs).

II. RADIO GALAXIES, ACTIVE GALACTIC NUCLEI, AND QUASARS

There are several points to discuss from the observational standpoint. What do these categories of objects have in common, what are the differences between them, what measurements can be made and with what limitations, and what physically meaningful correlations can be found?

In searching for correlations, there is the ever-present caveat to beware of selection effects, and therefore to attempt to find samples that are complete in one respect or another. Regarding radio sources, a tractably small yet sufficiently diverse sample is the 3CR catalog (Bennett 1962), consisting of sources with radio power $\geq$ 9 Jy. Optical observations of the QSOs in this sample have been complete for some time; the radio galaxies are so much fainter that it has taken decades to achieve an almost complete set of optical identifications of those not in very low galactic latitudes (cf. Smith et al., 1976). Spectroscopic observations of these very faint objects are necessary before one can do any work on analyzing their physics--attempts to assign redshifts to optically unexamined objects result in misleading theoretical analyses. After many years of painstaking and careful work, Spinrad and collaborators (Spinrad et al., 1985) have recently produced an almost complete set of spectroscopic observations, which will be a goldmine for theoretical analyses, interpretations, and cosmological studies.

Limited areas of the sky have been searched for optical identifications of QSO's, and at radio wavelengths, to faint limiting powers. The HEAO catalog provides a catalog of X-ray emitters from which the attempt to separate high galactic latitude sources into extragalactic and galactic objects is feasible.

The search for correlations in the properties of QSOs is difficult and often frustrating. The lack of a general correlation between apparent magnitude and log (redshift) is only too well known (cf. Hewitt and Burbidge 1980; Barbieri et al. 1982, figure 4). Correlations between X-ray and radio luminosities of QSOs have been shown to exist (Zamorani et al. 1981), but correlations between line strengths and X-ray luminosities in a sample chosen to have a large spread in X-ray luminosities and to contain both radio-loud and radio-quiet QSOs have not been found (Bradley 1985).

a) Physical Properties Common to RGs, AGNs, QSOs

Common properties are that all these classes have an energy source (the most likely being ultimately gravitational in origin) in a very small volume. The central "engine" produces accelerated particles, and the relativistic leptons can be recognized by the non-thermal synchrotron emission they produce.

Surrounding the central energy source there is usually ionized gas, recognized by thermal radiation. This gas is distributed non-uniformly; usually clouds of relatively high electron density (Ne $\sim 10^{10}$ cm^{-3}) with a small filling factor are surrounded by a lower-density, higher-temperature medium in which forbidden lines are produced. Seyfert galaxies exhibit the highest ionization in forbidden lines--up to [Fe X] in NGC 4151. Outward-directed beams of relativistic leptons produce radio emission in lobes which may be symmetrically placed either side of the central object, or which may be one-sided jets, or which may be bent or curved as though interaction with an intergalactic medium has occurred. Examples of these radio structures were described at this conference by Martin Rees.

Physical quantities which can be measured, besides morphological structure, are: optical apparent magnitudes at a selected wavelength, redshifts from optical or UV spectral emission lines, properties of the emission lines including their intensities and profiles, X-ray luminosities, radio fluxes.

The coexistence of electron beams (from collimated radio emission), X-ray beams, and "streaks" of thermal emission from hot gas or young stars can be well seen in the nearest strong radio galaxy NGC 5128 (Centarus A), as was shown by Martin Rees earlier in this conference (cf. Burns et al. 1983).

The recent work by Spinrad et al. (1985), in which 3CR radio galaxies with redshifts up to $z = 1.8$ have been measured, shows there are clearcut spectral differences between these and QSOs. First, the spectral lines are much narrower in RGs than in QSOs (smaller velocity dispension in the emitting gas). Second, [OII]λ 3727, which is quenched by electron collisional de-excitation at fairly low electron densities, is strong in radio galaxies but generally weak or absent in QSOs (e.g. 1641+399 and NRAO 140, Bradley 1985). HeII λ1640 is strong and sharp in the radio galaxy 3C256, and is not always seen in QSOs.

Spinrad et al. (1985) show in their Figure 1 a comparison between the histogram of redshift distribution between QSOs and RGs in the 3CR catalog. Both terminate at $z \sim 2$; this may be observational limitation in the case of the RGs because of their extremely faint optical emission, but is clearly an inherent property of the 3CR strong-source radio QSOs, since other radio catalogs have produced QSOs with $z \sim 3.8$ (Peterson et al. 1982).

QSOs themselves exhibit a wide range of properties. As an example, I describe a search using an objective-grating-prism (grism) at the prime focus of the Kitt Peak National Observatory Mayall telescope for QSOs with $z \sim 2$. Two areas of sky were searched, each about 1 square degree, one centered on a rich cluster of galaxies, A2151, in the Hercules supercluster, and one off the field of the cluster (Burbidge et al. 1985). Searches for radio-quiet QSOs are especially successful in finding objects with $2 < z < 3.3$, for which the Lyman-α hydrogen line, usually the strongest emission line seen in QSOs, falls in the observable region. Of 20 objects in the Hercules region, five with redshifts $z \sim 3$ had such strikingly different line profiles and relative strengths that they will provide challenging material for study of a set of QSOs in a small area of sky and a small range of redshift.

If we turn to the Seyfert nuclei, we see further striking differences between these objects and QSOs. Line profiles of permitted lines (Hα) can reach a Doppler width corresponding to Δv = 18,000 km/sec, and one such object shows strong narrow [Fe X]λ6374 and [Fe VII]λ6087 (Cohen 1985). Rapid continuum variability is found in both Seyferts and some QSOs, but, while short-time scale variations in permitted lines in Seyferts are well known, results on possible line variability in QSOs are still inconclusive.

b) Bulk Ejection from QSOs

Evidence for bulk ejection of matter at high velocities from active extragalactic objects is important when we make comparisons with ejection from galactic objects, novae, supernovae, and SS433 and possibly other such evolved binaries.

There is a class of QSOs in which the normal emission lines are accompanied by broad absorption troughs on the short wavelength side. The longest-known and best-studied object of this class of broad absorption-line QSOs (BAL QSOs) is PHL 5200 (Junkkarinen et al. 1983). Widths of the absorption troughs indicate outflow velocities of 30,000 km/sec, even in some extreme cases 66,000 km/sec, or more than 0.2c (Foltz et al. 1983). Such velocities may be compared with the typical 5000-10,000 km/sec ejections seen in supernovae.

Models of optically-thick outflow (Junkkarinen 1983) have shown from the observed line profiles that the outflow cannot be spherically symmetric. It could be in jets, conical outflow, a break up of disk-like structure. The absorbing material must have a small covering factor as seen from the inner clouds that produce the fairly normal emission lines, and the inner source of continuum radiation.

Until recently, it was thought that this phenomenon occurs only in rather high-redshift QSOs, with a frequency still imperfectly determined of between 1% and 10%. However, a case of outflow at 14,500 km/sec in a QSO with the relatively low z of 1.2 has recently been found (Wilkes 1985). Since this observation was made from the ground, with the University of Arizona 90-inch telescope, only CIV λ1549 was detected. In higher-redshift objects all the resonance lines display broad troughs - CIV λ1549, SiIV λ1397, NV λ1240, Lyα, and OVI λ1035.

c) Bulk Ejection from Other Active Galactic Nuclei

Small jets, usually seen as "blue jets" close in to the nuclei of radio galaxies, have been detected in a number of cases. An interesting case of a possible jet detected spectroscopically in the UV spectrum of the active Seyfert galaxy NGC 4151 has been described by Ulrich et al. (1985). Spectra taken with the International Ultraviolet Explorer showed two unidentified emission features, variable on a time scale of several days, flanking CIV λ1549. If they represent a jet seen in CIV λ1549 with an approaching component and, on the far side, a receding component (as in SS433), the line-of-sight outflow velocities would be -6100 and +8500 km/sec.

d) Do QSOs Have a Limiting Redshift?

Studies of the distribution of redshifts of QSOs have long displayed a peak around z = 2, mainly caused by the optically-discovered radio-quiet QSOs because of the easy visibility of Lyα λ1216 between z = 2 and 2.5 (Osmer 1982), see also histograms by Hewitt and Burbidge (1980)). Beyond z = 2.5, a precipitous decline in numbers of QSOs is seen. It took 10 years for the "record" redshift of z = 3.5 for OQ172 to be overtaken by two southern hemisphere QSOs, the largest redshift now known being 3.8 (Peterson et al.

1982). New histograms by Hewitt and Burbidge, to be presented at I.A.U. Symposium No. 119 in December 1985, in Bangalore, display these features very clearly.

There have been several speculations as to the cause of the precipitous decline. These include: this redshift corresponds to the epoch of galaxy formation; there is luminosity evolution in QSOs; regions at higher redshift are obscured by dust. The answers are not in, nor are likely to be until we have a better understanding of the relationship between galaxies and QSOs.

e) Are there Non-Cosmological Redshifts?

It is not fashionable to accept the existence of non-cosmological redshifts and the association of high-redshift active objects with low-redshift-galaxies. However, Arp and co-workers have gathered a significant amount of data on this controversial topic. The best-studied case is NGC 4319 and Markarian 205; in the presentation I showed slides taken from the work of Arp (1985), Wehinger and Wyckoff (1981), and Sulentic (1983); unfortunately these cannot be reproduced here. It seems, however, clear that there is a faint luminous bridge extending from Mrk 205 ($z = 0.07$) toward the nucleus of NGC 4319 ($z = 0.006$). What the nature of this luminous material is, and whether it really links the two objects, has not been resolved.

Other interesting cases are the aligned set of some 8 QSOs around NGC 3379 (Arp et al. 1979) and three QSOs within the arms of NGC 1073 (Arp and Sulentic 1979; Burbidge et al. 1979). A review of these apparent associations has been given by Burbidge (1981).

III. CONCLUSION

A thorny question in cosmic-ray physics is that of whether there is an extragalactic component of cosmic rays. The preceding sections have shown that components of the active extragalactic universe undoubtedly eject high-energy (relativistic) particles and bulk matter at high velocities approaching relativistic speeds, and these ejections must affect their extragalactic environment. There are distinct differences between Seyfert galaxies, quasars, and radio galaxies, but nevertheless they have in common an interior energy source which powers these phenomena. Of the radio galaxies, as Martin Rees pointed out in his introductory paper, NGC 5128 (CenA) is the nearest very active source, and it may be capable of emitting high-speed particles that reach the environment of our galaxy. I have not discussed the results of Very Long Baseline radio interferometry, since Rees showed examples, but the remarkable "superluminal" effects seen in e.g. 3C273 (cf. popular review by Field 1984) provide yet another indication of relativistic ejection at high Lorentz factors.

It seems not unlikely that the highest-energy cosmic rays may have an extragalactic origin, and further study of Centarus A could throw light on this controversial question.

REFERENCES

1. Arp, H. C. 1971, Astrophys. Lett., 9, 1.
2. Arp, H. C. 1985, private communication.
3. Arp, H., Sulentic, J.W. 1979, Ap. J., 229, 496.
4. Arp, H., Sulentic, J.W., and Tullio, G. di 1979, Ap. J., 229, 489.
5. Barbieri, C. et al. 1982, Mem. Soc. Astron. Italiana, Catalogue.
6. Bennett, A. S. 1962, Mem. Roy. Astron. Soc., 68, 163.
7. Bradley, S. E. 1985, Ph.D. Thesis, U. Calif. San Diego.
8. Burbidge, G. 1981, Ann. New York Acad. Sci., 375, 123.
9. Burbidge, E. M., Junkkarinen, V., and Koski, A. T. 1979, Ap. J., 233, L97.
10. Burbidge, E. M., Smith, H. E., Junkkarinen, V. T., and Hoag, A. A. 1985, Ap. J., 288, 82.
11. Burns, J. O., Feigelson, E. D., and Schreier, E. J. 1983, Ap. J., 273, 128.
12. Cohen, R. D. 1985, Ap. J., in preparation.
13. Field, G. 1984, Mercury, 13, 98.
14. Foltz, C., Wilkes, B., Weymann, R., and Turnshek, D. 1983, Pub. Astron. Soc. Pacific, 95, 341.
15. Hewitt, A. and Burbidge, G. 1980, Ap. J. Suppl., 43, 57.
16. Junkkarinen, V. T. 1983, Ap. J., 265, 73.
17. Junkkarinen, V. T., Burbidge, E. M., and Smith, H. E. 1983, Ap. J., 265, 51.
18. Osmer, P. 1982, Ap. J., 253, 28.
19. Peterson, B. A., Savage, A., Jauncey, D. L., and Wright, A. E. 1982, Ap. J., 260, L27, 1982.
20. Shanks, T., Fong, R. and Boyle, B. J. 1983, Nature, 303, 156.
21. Smith, H. E., Spinrad, H., and Smith, E. O. 1976, Pub. Astron. Soc. Pacific, 88, 621.
22. Spinrad, H., Djorgovski, S., Marr, J., and Aguilar, L. 1985, preprint and Pub. Astron. Soc. Pacific, in press.
23. Sulentic, J. W. 1983, Ap. J., 265, L49.
24. Ulrich, M. H. et al. 1985, preprint.
25. Wehinger, P.A. and Wyckoff, S. 1981, Sky and Telescope, 61, 200.
26. Wilkes, B. J. 1985, Ap. J, 288, L1.
27. Zamorani, G. et al. 1981, Ap. J., 245, 357.