INFRARED, OPTICAL, AND X-RAY PROPERTIES OF THE NUCLEI OF NEARBY GALAXIES

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GENERAL CONSIDERATIONS

The term "nearby galaxies" is not very precise. If we restrict ourselves to galaxies within the local group, we are really only talking about our Galaxy, M31 and M33. Since the Galactic Center has been reviewed extensively by Oort in Annual Reviews (1977), and I feel that there is nothing exceptional to say about the nuclei of M31 and M33 as far as phenomena other than their stellar content and central dynamics are concerned, to discuss interesting properties we must consider more distant objects. If we go out to the distance of the Virgo cluster, we already include objects such as NGC 5128, M82 and M87. Each of these galaxies shows or was claimed to show evidence of different kinds of violent nuclear activity. Indeed, it is obvious that within the volume occupied by the supercluster (whether or not it is really a physical entity) there must be many galaxies in which nuclear activity can be detected.

While it may be stretching things a little, the organizers have implied that NGC 1275 might be considered a "nearby" galaxy for the purposes of this discussion. Out to the distance of NGC 1275 (about 100 Mpc) there must be $\sim 10^5$ galaxies. Clearly within this sample all types of nuclear activity should be detectable.

How does one define nuclear activity of a special kind?

The distinction that I would like to make is between energy release processes which take place through the evolution of normal stars in low density systems, and processes which are more exotic than this and can only take place either through the evolution of high density stellar systems or from new physics.

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This leads to two obvious distinctions which can be made observationally. For normal stars the largest energy release which can occur rapidly is in a supernova explosion. Thus, any phenomenon which can be shown to have released more than 10^{53}-10^{54} erg cannot be due to a single normal star. A second distinction is associated with the position in the galaxy where this outburst occurs. If only a single star is involved, the outburst can take place anywhere in the galaxy. However, activity involving more exotic processes is only likely to occur in the mass center -- the true nucleus.

A fundamental problem which remains in this exciting field is the very tenuous link between theory and observation. A simple view based on the observations originally put forward by Burbidge, Burbidge and Sandage (1963) is that there are such a wide variety of manifestations of activity in the nuclei of galaxies that it could be supposed that all galaxies have active nuclei throughout their lives, and that it is only the level of activity and the problem of detection that are the variables from system to system. We were thinking in those days that the violent nuclei were the results of single violent events (explosions) whose effects could last for $\sim 10^6$-10^8 years, but that such events could repeat.

The models for violent activity which have been developed are of several kinds:

(a) Multiple supernovae and their remnants (pulsars), with a rate of outbursts chosen to explain the observed level of activity.
(b) Energy released by a massive rotating superstar (spinar) similar in some ways to a pulsar.
(c) Energy released by matter falling into a massive black hole and/or surrounding accretion disk.
(d) Energy pouring out of a singularity (white hole) in the form in which it is observed.

Each of these schemes has its advocates and its periods of popularity. Currently (c) is the most popular and (d), because it involves modifications of physics and has not been worked out in any detail, is the least popular.

But when we begin to ask how far these theories go in explaining what we see, and even more, in making predictions which would discriminate between models, the answer is that very little progress has been made. We observe some, or all, of the following:

(i) Nonthermal optical and radio continua which are generally thought to be incoherent synchrotron radiation.

(ii) A hot gas emission-line spectrum, the lines being exceedingly broad ($\lesssim$ 10 000 km sec^{-1}) almost certainly due to mass motions.

(iii) Very large infrared fluxes extending in some cases to 100-300 μ. In many cases the IR flux is thought to be thermal.

(iv) The ejection of large masses of gas, and in some cases what appear to be coherent objects.

(v) Extended radio sources.

One of the reasons why it is so difficult to relate the "machine" to its observational consequences is that the scales are so different. Since gravitational energy must be the ultimate energy source in all conventional models, we believe, without understanding very clearly, that the energy must be released fairly close to the Schwarzschild radius which, even for a 10^{10} $M_{\odot}$ object, is only $\sim 10^{15}$ cm and is proportional to the mass. Now the observational phenomena which we have to explain take place on scales which range from sizes that may be as small as this, up to dimensions of kiloparsecs (for optical phenomena) and megaparsecs (for radio phenomena). But only from measures of variability and light travel time can we measure small sizes optically at present (down to $\sim 10^{15}$ cm) and very little is known about light variations in the nuclei of galaxies. VLBI techniques allow us to measure 10^{-3} to 10^{-4} arc sec corresponding to scales $\leq$ 0.5 pc for distances $\leq$ 100 Mpc, and the size of the very small resolved radio source in the Galactic Center $\simeq 7 \times 10^{13}$ cm may be highly significant. If this were the ultimate size of the "machine," it would tell us a great deal. However, not only is this a very weak source, which may be due to a single star, it is also possible that the more powerful nuclei may contain machines which are intrinsically much bigger.

Ideally, in studying the nuclei of nearby galaxies, we would like to test the predictions of the various theoretical models against the observations, or failing this, attempt to rule out some theories on the basis of observations. Unfortunately we are not anywhere near the stage where this can be done. The procedure that is still being adopted by theoreticians is to adopt a model, e.g. a massive black hole surrounded by an accretion disk, and then attempt to speculate on a scenario which will give some of the observed properties. Since there is usually a wealth of free parameters, there is no quantitative way to estimate the plausibility of a chosen model.

In this lecture I cannot improve on this situation. I will simply briefly discuss a few observational discoveries which relate to the nuclei of galaxies.

SOME OBSERVED PHENOMENA

Obscured Nuclei

There are two well known nearby galaxies which have been thought to have active nuclei which are heavily obscured by dust. They are NGC 5128 and M82.

NGC 5128 was long ago identified as a powerful extended radio source, and the inner double lobe structure showed that more than one outburst was involved. However only recently has the nuclear structure been studied at infrared, X-ray, and γ-ray wavelengths. The object is powerful and rapidly variable, but since it will be discussed by M. Rees I shall not mention it further.

M82 has had a chequered history. It was one of the original galaxies in which it was believed that a violent explosion had occurred, the evidence coming from the radio properties, the velocity field which suggests ejection along the rotation axis, and high polarization of the continuum radiation from the optical filaments extending above and below the plane which was interpreted as optical synchrotron radiation. The discovery that there was a high degree of polarization in the Hα emission lines from the filaments meant that another explanation for the polarization was required. Solinger, Morrison, and Markert (1977) have now concluded that all of the evidence for an explosion has effectively been removed, and their arguments at this point should be taken very seriously. Studies of the central region of M82 in the near and far infrared and also in radio wavelengths (Raff 1969; Kleinmann and Low 1970a, b; van den Bergh 1971; Hargrave 1974; Kronberg and Wilkinson 1975) show that there is no evidence for a powerful nonthermal nuclear source. The radiation from the central region at these wavelengths is resolved into a number of discrete sources with a highly complex pattern. They may simply be due to heavily obscured O and B associations similar in some respects to the pattern in our own Galactic Center. Of course the existence of a very weak nonthermal source is not excluded.

Probably the most difficult problem which we encounter in reinterpreting the evidence for a galactic explosion in M82 is to find an alternative explanation for the velocity field. Solinger et al. have argued that it can be explained by supposing that the galaxy is drifting through a large cloud of intergalactic dust with the dust grains acting as moving mirrors. While this explanation is ingenious, it is still not very satisfactory, since a very large cloud of dust of unspecified origin is required.

But on balance we must probably now exclude M82 from the class of galaxies in which violent activity is seen.

Powerful Infrared Sources in Galaxies

Several years ago Low and his associates (Kleinmann and Low 1970a, b; Aumann and Low 1970; Low 1970) measured the infrared fluxes out to $\sim 25\ \mu$ in a number of bright galaxies and obtained very large luminosities which they concluded were due to nonthermal processes in the nuclei. These observations were not all confirmed. However, while the initial measurements may have had problems, studies carried out since 1970 by Rieke et al. (1973), Clegg et al. (1976), Low and several other groups (Rieke and Low 1972; Penston et al. 1971, 1974; Hildebrand et al. 1977) show that large infrared fluxes are indeed present. The observations have now been extended in a few cases out to wavelengths as long as 1 mm. It is clear that in many cases the luminosities out to $\sim 25\ \mu$ are comparable to or greater than the total optical luminosities of the galaxies.

Among the galaxies which have been detected in this way are the classical Seyfert galaxies NGC 1068 and NGC 4151, M82, NGC 253, NGC 5236, and others.

There are two possible mechanisms operating to give the infrared flux:

(i) A nonthermal process, meaning that it is likely to be incoherent synchrotron or Compton scattered radiation,

(ii) Thermal radiation from dust.

If (ii) is operating, the grain temperatures must be low ($\lesssim 100°$ K) and thus the sources must be extended. Consequently we would not expect to see variations in flux in the infrared. On the other hand, if the radiation is nonthermal, we expect that it does arise in the machine in the nucleus. Even if the radiation is thermal, however, it may well be that the source which is heating the dust is nonthermal. As was pointed out by Rieke and Low (1972) very considerable problems are encountered if we attribute the energy source to stars. For large luminosities $\sim 10^{44}$-10^{45} erg sec^{-1} very large numbers ($\sim 10^8$) of high

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luminosity O and B stars would be required. They would comprise a large fraction of the mass in the central region of the galaxy. However, their evolutionary lifetimes are very short ($\sim 10^6$ years). Such luminosities could not be maintained for more than a small fraction of the lifetime of the galaxy. Thus, the existence of such high infrared luminosities would only be expected in rare circumstances. Thus the fact that nearby galaxies are commonly found to have large infrared luminosities, suggests that the radiation is ultimately of nonthermal origin.

As the evidence stands at present, the only good case for variability in the infrared is NGC 4151. It appears that NGC 1068 has shown no variations and this source is extended.

In some cases the form of the infrared spectrum strongly suggests a thermal origin.

A serious problem associated with the large far-infrared luminosities is the large amount of dust and interstellar matter which is apparently required. In a recent study, Hildebrand et al. (1977) have concluded that to explain far infrared fluxes of 1.2×10^{45} erg sec^{-1} and 6×10^{43} erg sec^{-1} in NGC 1068 and NGC 253 respectively; the mass of dust required is $10^8\ M_\odot$ in NGC 1068 and $8 \times 10^6\ M_\odot$ in NGC 253. Assuming a gas-to-dust ratio = 100, this gives total amounts of diffuse matter of $10^{10}\ M_\odot$ in NGC 1068 and $8 \times 10^8\ M_\odot$ in NGC 253. Now rotation curves are available for both of these galaxies (Burbidge, Burbidge and Prendergast 1959; Burbidge et al. 1962) and thus an upper limit to the mass contained in the same volume can be obtained. In both cases the total mass is comparable with, or considerably less than, the mass apparently required to explain the infrared observations. There are three possible ways to resolve this dilemma.

(1) To argue that the radiation is nonthermal. However, the spectra appear to have rough blackbody forms, so that this is unlikely.

(2) To argue that the gas-to-dust ratio is much less than 100.

(3) To suppose that the dust is a much more efficient radiator than is generally supposed, i.e. $Q(\nu)$, the emissivity of the grains, is very different from the values assumed.

Probably both (2) and (3) are important. Almost certainly the emissivity of the grains is more efficient, than has been assumed so far. But at present the observations present a puzzle.

X-Ray Emission from Seyfert Galaxies

Until very recently very few of the classical (nearby) Seyfert galaxies were known to be X-ray emitters. However, recent results from the Ariel V Sky Survey instrument (Elvis et al. 1977) show that many Seyfert galaxies are powerful X-ray sources. Classical Seyferts which are now identified include NGC 4151, NGC 3227, NGC 5548, NGC 6814, and NGC 1275. In total 15 Seyferts are now reported as X-ray sources. However, the others are further away and do not fall into the loose category of nearby Seyfert galaxies.

The luminosities lie in the range 10^{43}-10^{44} erg sec^{-1} in the photon energy range 2-10 keV (NGC 4151 is a strong source at $\sim$ 100 keV), and are thus 10 to 100 times more energetic than the optical fluxes from Seyfert nuclei.

This puts further demands on the energetic properties of the central machine.

It is much too early to say anything definitive about the mechanism of X-ray generation. The discoverers argue that the X-ray power is correlated with the IR and continuum optical flux and with the luminosity in Hα. They conclude that it arises in a region < 0.1 pc from the center. Possible mechanisms are bremsstrahlung, the hot gas arising from shock heating in the highly turbulent center where the broad lines arise, or Compton radiation from optical or IR photons generated by the synchrotron process. They favor the latter process.

Ejection of Large Gas Masses from Nuclei

One of the earliest indicators of violent activity in galactic nuclei was the evidence that matter in considerable amounts is being ejected at high velocities. Different kinds of observations suggest this. Here are some examples.

(a) High velocities in Seyfert nuclei (1000-10 000 km sec^{-1}) which are far greater than the escape velocities.

(b) The apparent explosive ejection in M82 which may now need to be reinterpreted.

(c) Ejection of a large mass of gas in NGC 1275 with a line of sight velocity difference of $\sim$ 3000 km sec^{-1} with respect to the center. The total mass is of order 10^8 $M_\odot$. Attempts

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to reinterpret the observation in terms of a colliding or intervening galaxy are, in my opinion, unconvincing.

(d) Similar evidence for a large ejection in the radio galaxy DA 240 which has a large jet. Gas in the jet has a line-of-sight velocity some 3000 km sec^{-1} less than the velocity of recession. DA 240 does not lie in a cluster of galaxies.

(e) The double structures in the emission lines in N systems like 3C 390.3, 3C 227, etc. are probably due to phenomena similar to those seen in NGC 1275 and DA 240. The separation of the emission line peaks is $\sim$ 3000-4000 km sec^{-1}.

(f) If the absorption-line systems in the spectra of QSOs are intrinsic to the objects, as seems likely, they indicate that gas shells are being ejected with velocities typically of order 0.1c.

(g) Ejecta from M87. The jet appears to be made up of a series of highly compact synchrotron sources. Velocities and masses are not known.

(h) Shreds of gas ejected from NGC 5128.

(i) Non-circular motions observed in the central regions of many spiral galaxies are most likely to be due to explosive ejection from the nuclei.

CONCLUSION

No attempt has been made here to review all of the many recent observations of the activity in the nuclei of nearby galaxies. Instead we have chosen to discuss a few phenomena which have recently been discovered. In each case the new observations show that nuclei are even more energetic than we have believed before.

The connections between theory and observation are still very tenuous. However, it does appear likely that almost every galaxy contains a "machine" in its nucleus which is able to release energy in many exotic forms, and which is active for a large fraction of the life of the galaxy, though it may, for long periods, operate at a low level of activity.

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DISCUSSION FOLLOWING REVIEW IV.3 GIVEN BY G. BURBIDGE

OORT: In connection with your enumeration of the few cases of ordinary galaxies with direct evidence for expulsion of gas from the nuclear region one should mention the phenomena in our own Galaxy, in which among other phenomena indicating such expulsion there is the massive ring of molecular clouds at about 190 parsecs from the center expanding at a velocity of 150 km/s. In this case there is not much room for doubt that we are witnessing gas expelled from a small nuclear region, and in such quantity that quite high energies must have been involved.

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