III. AGN THEORY AND MODELS

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Energy Sources and Physical Processes in Active Galaxies

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Abstract.
The galaxy Markarian 231 is reviewed as a prototype that includes all physical processes associated with active galaxies. It contains both a starburst and an AGN which are highly obscured by dust. Its luminosity at various wavelengths is used to summarize how such a galaxy would appear at high redshift, as observed with missions such as HST, AXAF, and SIRTF. The conclusion is that Markarian 231 provides an excellent example for comparing low redshift and high redshift phenomena.

1. Introduction

It is exciting and rewarding to look back personally over 30 years of research on active galaxies that was stimulated by discoveries at the Byurakan Observatory. The Markarian survey was the initial extragalactic survey that attempted to sort objects spectroscopically. It was undertaken with commendable scientific motivation, which was to locate in other galaxies examples of ejections from galactic nuclei that Ambartsumian felt were the key to understanding galaxy formation. The survey proved to be a treasure trove for locating galaxies with intense, non-stellar sources of luminosity in their nuclei, galaxies similar to the very small number of Seyfert galaxies known at the time. It was these Markarian galaxies which provided vital connecting links to the characteristics of quasars. In the decades since, the Markarian galaxies have provided prototypes for many objects classified as "active galactic nuclei" (AGN).

Markarian's survey not only found many examples of active nuclei, but also discovered vigorous regions of star formation that could be identified with the "superassociations" championed by Ambartsumian. Now labelled "starburst" galaxies, these locations of intense star formation are a vital form of galaxy activity, especially important when attempting to understand how galaxies form primordially. Because we have learned that the luminosities of starbursts can exceed the luminosities arising from central nuclei, and that starbursts are often intimately associated with other forms of activity in and near the centers of galaxies, it is appropriate to include both starbursts and AGN when summarizing the physical processes and energy sources in "active galaxies".

The luminosity function of the Markarian starburst galaxies gave us an early census of star formation within the nearby universe (Huchra 1977). Since then, a great deal of observational effort has developed an overall picture of star formation as it can be seen through the universe back to redshifts of approximately

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four (Madau et al. 1996). Similarly, the Markarian survey yielded the Seyfert galaxy luminosity function in the nearby universe for comparing with quasars elsewhere (Weedman 1986). The survey initiated the low dispersion spectral survey technique that led eventually to assembling the quasar data which define quasar evolution. Stimulated by the Markarian surveys, similar objective prism surveys with Schmidt Telescopes began at Cerro Tololo and the Anglo-Australian Observatory (Smith 1983). In addition to finding galaxies, these surveys showed the surprising ease of finding quasars based on the emission lines seen in these spectra. Similar surveys were then extended to fainter magnitudes using wide-field grism spectroscopy with larger telescopes, and the combined results definitively show the evolution of the quasar luminosity function (Schmidt, Schneider and Gunn 1995).

The Markarian galaxies came at a crucial time because they provided an initial list for subsequent study in the ultraviolet and infrared wavelengths that soon became accessible from space. As a consequence, this exceptionally broad wavelength coverage led to observational definitions of highly diverse phenomena. Now, these can be unified, and it is possible to review all of the fundamental processes that have been discovered within active galaxies by describing a single Markarian galaxy which shows examples of all such processes. This galaxy is Markarian 231, and my review of physical processes will use Markarian 231 as a case study to demonstrate the exceptional range of observational techniques and conclusions gained in three decades of study. As a guide to interpreting future observations, I will also summarize how this prototype galaxy would appear to the Hubble Space Telescope (HST), the Advanced X-Ray Astrophysics Facility (AXAF), and the Space Infrared Telescope Facility (SIRTF), if located at a redshift of 3.

From the perspective of an observer of Markarian galaxies, the most dismaying development was the eventual realization that the ultraviolet luminosity which we observed is only a small part of what is intrinsically produced. Dust is taking away most of the ultraviolet. It is probably fortunate that the infrared observers stumbled on starburst galaxies after Markarian. Had the extent of dust obscuration been known, an observing proposal to look for galaxies based on their ultraviolet continuum would have been skeptically received! I will review the evidence for these absorbing effects to emphasize that future progress will depend crucially on our abilities to understand and penetrate this obscuration.

2. Markarian 231 and Physical Processes in Active Galaxies

This single Markarian galaxy can be used as a prototype to illustrate all of the crucial physical processes and energy sources in and near galactic nuclei. Originally, this galaxy seemed very strange to Ed Khachikian and me when defining the Seyfert 1 galaxies. It was the only one known with conspicuous absorption lines (spectrum in Khachikian and Weedman 1974). Now, we know that it has virtually all of the varied characteristics associated with differently classified active galaxies; the fact that a straightforward and consistent interpretation of all these characteristics can be summarized is an indication of the unity among the diverse processes of active galaxies. Markarian 231 contains young and old starbursts, contains an AGN with broad line region that is a strong Fe II emit-

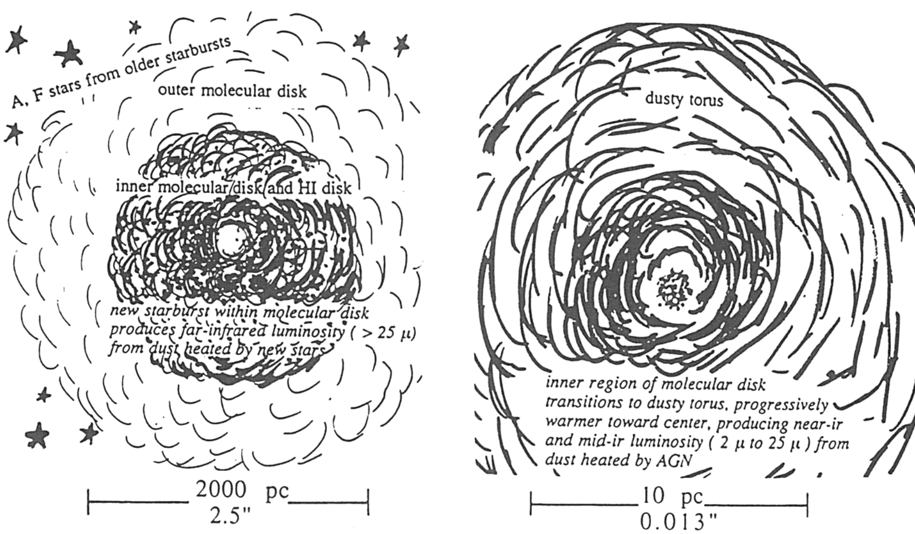

Figure 1. Markarian 231 on Kpc and pc scales.

ter, has extensive molecular clouds with super-starbursts, and is obscured by extensive dust absorption. As a consequence of the latter, it is a strong source from near infrared through far infrared and is a prototype for ultra-luminous infrared galaxies (ULIRG - Sanders et al. 1987). Like several such objects, it produces an OH megamaser (Baan, Haschick and Henkel 1992). Its AGN shows the X-ray, ultraviolet, and optical continuum characteristically attributed to a hot accretion disk. Complex, blue-shifted absorption in the optical and ultraviolet produces the characteristic spectrum of a BAL quasar, and it shows a variable radio jet from the nucleus. Markarian 231 has something for everyone! Because of the extensive observational material available at all wavelengths from X-ray through radio, it is possible to deduce simplified cartoons which consistently interpret the varied observational phenomena and which illustrate them to scale.

Markarian 231 is a large, irregular galaxy that is presumably disturbed because of a galaxy interaction (Hamilton and Keel 1987). This interaction or a previous one stimulated earlier starbursts, as revealed by the early star spectrum characterizing much of the outer regions (Boksenberg et al. 1977). Although its outer regions extend to tens of Kpc, it is in the central region in which the bulk of the luminosity is generated. My first view has a scale size of 3 Kpc, sketched in Figure 1. The key to this part of Markarian 231 is the large mass of molecular and HI gas that has accumulated within the central 3 Kpc. Downes and Solomon (1998) and Carilli, Wrobel and Ulvestad (1998) thoroughly describe this gas disk and emphasize that this is the fundamental source of most of the galaxy's luminosity. Downes and Solomon conclude that $4\times10^9\ M_\odot$ of new stars are present in the current starburst within the molecular disk; Carilli et al. estimate these stars to be forming at the rate of 60 $M_\odot yr^{-1}$. The far-infrared luminosity of this starburst dominates the bolometric luminosity, being

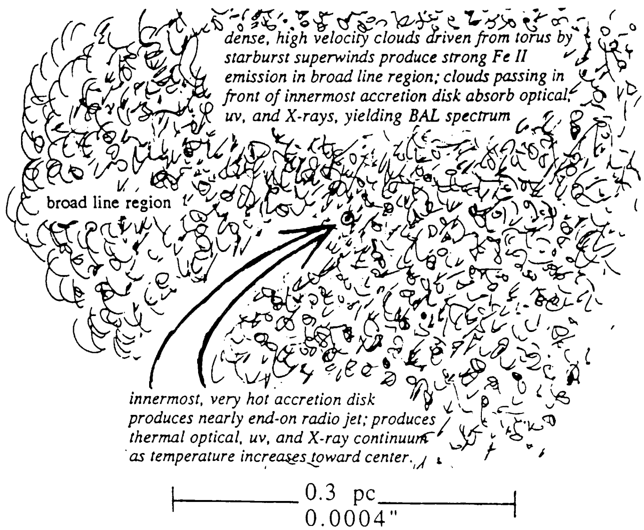

Figure 2. Markarian 231 on sub-pc scales.

responsible for about two-thirds of the 10^{46} erg s^{-1} which this ultraluminous galaxy generates.

The inner region of the molecular disk transitions to a "dusty torus" which is close enough to the AGN to be heated by it (also in Figure 1). Hot dust in the torus produces near infrared and mid infrared luminosity (Krabbe et al. 1997, Miles et al. 1996). Such a torus and its orientation are responsible for explaining the differences between Sy 1 and Sy 2 galaxies in various unified schemes.

Within the nearly face-on torus is the broad line region and the innermost accretion disk, as in Figure 2. The torus is a source of dense clouds, driven off by starburst superwinds. These clouds driven into the broad line region are unusually dense compared to those in many Sy 1, so they yield strong Fe II emission (Lawrence et al. 1997) while causing conspicuous absorption effects when they pass in front of the X-ray, uv, and optical continuum source. Because the clouds are boiling out above the center of the torus and in front of the accretion disk, the cloud absorptions show blueshifts relative to the galaxy, explaining the BAL spectral characteristics (Lipari, Colina and Macchetto 1994).

Markarian 231 has been detected in X-rays, in both ROSAT and ASCA bandpasses (Lawrence et al. 1997, Turner 1998), and in the ultraviolet, using HST (Smith et al. 1995). In these wavebands, also, this galaxy shows indicators of both starburst and AGN components. The soft X- ray ROSAT HRI detection (0.5 - 2 keV) is dominated by the extended starburst, but the higher energy ASCA flux (2 - 10 keV) seems to arise from the nucleus. The ultraviolet continuum from the nucleus is polarized but at shorter wavelengths is dominated by unpolarized light from the starburst.

An unresolved but variable radio source is observed in the center, with an extension implying a radio jet (Carilli et al. 1998, Smith, Lonsdale and Lonsdale 1998). The radio jet is that characteristic which is considered to be most intimately associated with a massive black hole. The total radio flux of 240 mJy is divided evenly between the AGN component and a more extended, presumably starburst component.

The unique spectral characteristics of Markarian 231, initially so puzzling, are thereby explained because the torus is face on while extending close enough to the AGN to produce obscuring effects. The AGN is heavily obscured but not so obscured as to hide its fundamental character. Light from the inner accretion disk and broad line region is not completely obscured, so it is classifiable as a Seyfert 1 galaxy. But the extensive amount of dense material close to the nucleus, and the energizing effects in the torus caused by the starburst, produce unusually thick and high velocity absorbing clouds which appear in front of the innermost accretion disk. Had there been less obscuring material in the inner torus, Markarian 231 would have been a more normally appearing Sy 1. Had the torus been more edge on, it would have been seen as a Sy 2. Had the torus been so thick as to block all signs of the AGN, Markarian 231 would have been classified as purely starburst. That the AGN dominates some characteristics and the starburst dominates others illustrates why it is often difficult to determine the ultimate source of luminosity for highly obscured objects.

3. Markarian 231 at High Redshift

Being a ULIRG makes Markarian 231 a feasible prototype for the optically-faint galaxies detected by the SCUBA submillimeter camera (Hughes et al. 1998) and by the Infrared Space Observatory (ISO) far-infrared surveys (Kawara et al. 1998). Some such detections probably are of dusty galaxies at $z > 2$. It is crucial to understand the dust content and energy sources of the high-redshift universe, so it is important to summarize how Markarian 231 would appear at such redshifts. (Markarian 231 has $z = 0.0422$. Results which follow are all based on a cosmology with $\Omega = 0.2$ and $\Lambda = 0$; if $\Omega = 1$, all fluxes given for redshift 3 would be brighter by a factor of 2.3.)

An object like Markarian 231 would be marginally detectable by AXAF at a redshift approaching 3. The 2-10 keV luminosity is approximately 10^{43}erg s^{-1} (Turner 1998). At redshift of 3, this would be redshifted into the 0.5-2.5 keV band; within this band, AXAF should have sensitivity in long pointings of about 3×10^{-16} erg cm^{-2} s^{-1}. Markarian 231 would have X-ray flux in this band of between 1.2×10^{-16} and 4×10^{-16} for $3 > z > 2$. Because it is the rest-frame 2-10 keV X-rays that are observed at high redshift, an X-ray detection of an obscured galaxy at such redshifts would be a strong indicator of the presence of an AGN.

The ultraviolet flux as observed at rest frame wavelength of 2030 $\AA$ is approximately 1.3×10^{-15} erg cm^{-2} s^{-1} $\AA^{-1}$ (Smith et al. 1995), all arising from an unresolved region. This rest wavelength corresponds to the wavelength at which a galaxy with redshift 3 would be observed in the F814 filter of the Hubble Deep Field (HDF). The flux of Markarian 231 at such a redshift would be 1.7 $\times 10^{-20}$ erg cm^{-2} s^{-1} $\AA^{-1}$. As an unresolved object, this flux would fall within an area of about 9 pixels in the HDF. The surface brightness within a 9 pixel area would be 1.2×10^{-18} erg cm^{-2} s^{-1} A^{-1} $arcsec^{-2}$. This is similar to the maximum surface brightnesses of the known high redshift starburst objects in

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the HDF (Lowenthal et al. 1997), as tabulated by Weedman et al. (1998). The difference, however, is that those starbursts are much larger in size and are easily resolved in the HDF. Markarian 231 would be a "blank-field" source based on ground-based optical images, because the flux at 8140 Å would correspond to a magnitude fainter than 27. This is consistent with the lack of optical detections of some SCUBA and ISO sources, if those sources are attributed to objects like Markarian 231 at $z > 2$.

With SIRTF, spectrometry will be available for $5\mu < \lambda < 40\mu$ and can determine redshifts based on broad PAH and silicate features. The ISO mission has shown us these strong spectral features in active galaxies (Moorwood et al. 1996). These features could be followed to high redshifts in order to identify very obscured galaxies whose redshifts cannot be determined optically. Within the NASA/IPAC Extragalactic Database, Markarian 231 has 8.4 μ flux of 1.1 Jy. Using this to determine a rest-frame luminosity, at $z = 2$ it would have observed 25 μ flux of 0.47 mJy; this flux should be within the range of SIRTF's spectrometer. The same rest-frame luminosity by $z = 3$ would have observed 33 μ flux of 0.21 mJy, which will be marginal.

An important use of radio observations will be to determine accurate positions, in search of faint optical identifications, for sources detected in the far infrared or submillimeter. Taking the total flux of Markarian 231 as 240 mJy at 20 cm with a flat spectral index (Smith et al. 1998), the 20 cm flux would reduce to 0.046 mJy at $z = 3$; this would be readily within current VLA detection capabilities.

4. Effects of Dust Obscuration

Most of what we know about starbursts and quasars at high redshift is based upon their appearance in the rest frame ultraviolet. This is troublesome because of the evidence for substantial dust obscuration. Many efforts have been made to apply dust extinction corrections to the observed ultraviolet spectra of both nearby and distant starburst galaxies by considering the shapes of these spectra (e.g. Meurer et al. 1997, Pettini et al. 1998). These corrections indicate that ultraviolet observations underestimate by factors of five or more the total luminosity of starbursts. A beautiful picture of Centaurus A from HST (http://oposite.stsci.edu/pubinfo/pr/1998/14/) indicates why applying such dust corrections is problematical; the starlight you correct is only the starlight you can see. Extinction corrections are applied to partially obscured but still visible stars. This is only a lower limit on the correction because of the many stars that remain completely hidden in the dust clouds.

If sufficient infrared observations are available to deduce the bolometric luminosity of the starburst, including dust re-radiation, the total luminosity can be compared to what emerges in the ultraviolet and can yield an empirical fraction for this emergent ultraviolet luminosity. In large measure because of the many Markarian galaxies detected both with IUE and IRAS, this comparison can be made for a sample of galaxies with detections in both wavebands. Using the bolometric fluxes from Schmitt et al. (1997), the IUE ultraviolet fluxes from Kinney et al. (1993), and the relation between ultraviolet and bolometric fluxes for star formation models such as those in Meurer et al. (1997), the intrinsic and observed ultraviolet fluxes can be deduced and compared for a sample of 24 local starburst galaxies, as described by Weedman et al. (1998). This result shows that, as a median value, only 10% of the intrinsic ultraviolet luminosity escapes from these starburst galaxies. This sample is subject to selection effects, the most dominant of which is the requirement of having a detected ultraviolet flux. Galaxies so obscured that IUE cannot see them are not included, so this sample underestimates the amount of dust obscuration for the entire local population of starburst galaxies.

Because of the large obscuration that can be demonstrated in local starbursts and is suspected in high redshift starbursts, it is obvious that determinations via rest-frame ultraviolet observations of the star formation rate (and, by similar arguments, of the AGN rate) are highly uncertain. This means that our census of physical processes and energy sources in the high redshift universe is woefully incomplete. It is crucial to determine how obscured are those objects already discovered at high redshifts. It is also necessary to know if other dusty objects at high redshifts are similar to objects which can be dimly seen via their rest-frame ultraviolet, or if the dusty objects are primarily a separate population. Gaining such a census requires infrared observations.

Acknowledgments. We have learned an extraordinary amount about active galactic nuclei and about star formation since those early days forty years ago when Victor Ambartsumian and Beniamen Markarian decided to hunt for unusual galaxies. I thank them and their Armenian colleagues for that contribution to astronomy and wish they could know the progress which has come about because of the pioneering ideas and observations originating at Byurakan Observatory.

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