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OBSERVATIONS OF AGN WITH LARGE TELESCOPES

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RESUMEN

Aquí describo cuatro cuestiones científicas apremiantes en lo referente a AGN que pueden ser abordadas empleando el telescopio de 10-m como el GTC. (1) La demografía de agujeros negros puede ser determinada mediante exploraciones profundas de longitudes de ondas múltiples (incluyendo rayos X) seguidas por espectroscopía del óptico e infrarrojo con un telescopio de la clase de 10-m. En la época de la actividad pico de AGN, alrededor de $z \sim 2$, la mayoría de los AGN será clasificada erróneamente por las exploraciones ópticas, ya que los más fuertemente oscurecidos solamente cuentan con emisión de la galaxia anfitriona en el óptico; si la galaxia es muy roja, la espectroscopía infrarroja resulta esencial. (2) Masas precisas de agujeros negros pueden ser determinadas utilizando la relación M_{BH}-σ. Esta puede revelar las tendencias en luminosidad con masa de agujero negro que hasta ahora no resultan aparentes. La evolución de la relación M_{BH}-σ con el corrimiento al rojo potencialmente constriñe modelos de formación de galaxias y de retroalimentación. La medición de σ requiere un telescopio de la clase de 10-m para todos los AGN excepto los más cercanos. (3) Imaginería óptica profunda de alta resolución puede revelar directamente las propiedades de la galaxia anfitriona de AGN, incluyendo los episodios de formación estelar. Con imaginería muy profunda, el GTC podría de esta manera indagar las escalas de tiempo relativas de la actividad de formación estelar a escala galáctica y de la acreción nuclear de agujeros negros, revelando así la conexión entre agujeros negros y galaxias. (4) Finalmente, imaginería profunda con alta resolución espacial, en un amplio rango de longitudes de ondas desde el infrarrojo al óptico, promete esclarecer las condiciones físicas en jets relativistas y ofrecer importante información para llegar a entender sus procesos de emisión, su fuerza cinética y el contenido de materia.

ABSTRACT

Here I describe four compelling AGN science questions that can be addressed with a 10-m telescope like the GTC. (1) Black hole demographics can be determined through deep multiwavelength surveys (including X-rays) followed by optical and infrared spectroscopy with a 10-m class telescope. At the epoch of peak AGN activity, around $z \sim 2$, most AGN will be mis-classified by optical surveys, but are revealed through their X-ray activity. The most heavily obscured have only host galaxy emission in the optical; if the galaxy is very red, infrared spectroscopy is essential. (2) Accurate black hole masses can be determined using the M_{BH}-σ relation. This may reveal trends in luminosity with black hole mass that so far are not apparent. The evolution of the M_{BH}-σ relation with redshift potentially constrains models of galaxy formation and feedback. Measurement of σ requires a 10-m class telescope for all but the nearest AGN. (3) High-resolution, deep optical imaging can directly reveal AGN host galaxy properties, including episodes of star formation. With very deep imaging, the GTC could thus probe the relative time scales for galaxy-scale star-formation activity and nuclear black hole accretion, thus illuminating the black hole-galaxy connection. (4) Finally, deep imaging with high spatial resolution, at a wide range of wavelengths from the infrared through optical, promises to illuminate the physical conditions in powerful kiloparsec-scale relativistic jets, and to offer important information for understanding their emission processes, kinetic power, and matter content.

Key Words: **GALAXIES: ACTIVE — GALAXIES: JETS**

1. INTRODUCTION TO AGN

Large telescopes are essential for studying the actively accreting supermassive black holes that power Active Galactic Nuclei (AGN). AGN are rare — only 1-30% of all galaxies, depending on luminosity — so on average, they are very distant and often relatively faint (say, compared to stars). Figure 1 shows a relatively nearby and very well known example, 3C273 ($z = 0.158$, $D \sim 750$ Mpc). Its nuclear luminosity outshines its host galaxy (which can be seen in high-resolution HST images), and a tightly collimated jet extends for ten or more kiloparsecs on one side of the AGN nucleus, which we discuss fur-

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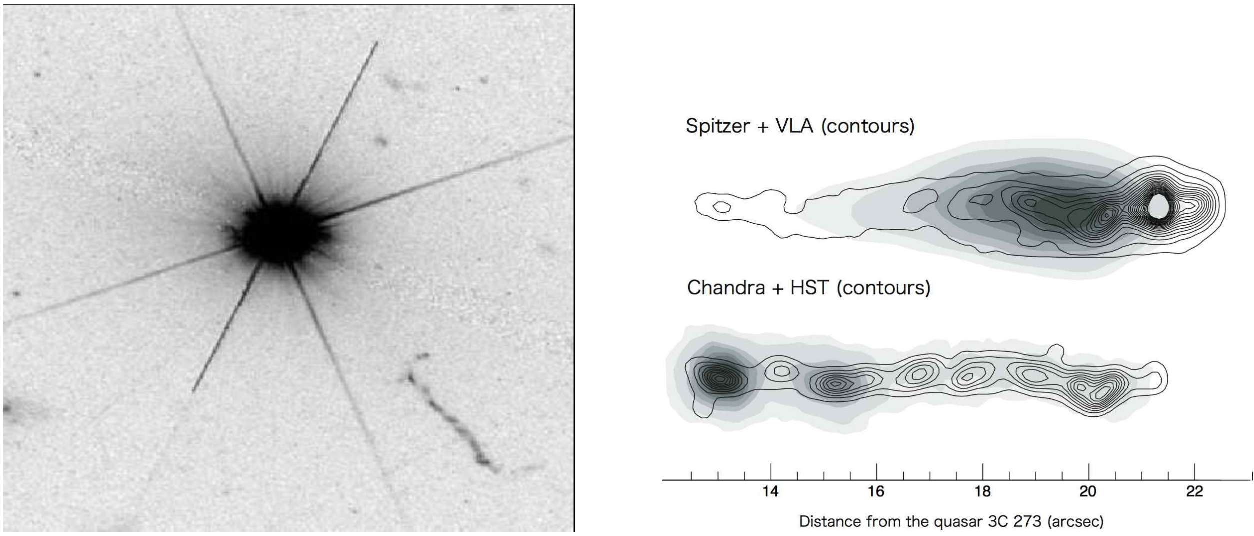

Fig. 1. (a) Optical image of 3C273, showing the extended jet. (b) Expanded, multiwavelength view of the 3C273 jet (Uchiyama et al. 2006), which extends from 13-23″ from the quasar core. Combined data from Spitzer deconvolved 3.6 mm in red, HST UV excess [0.3 mm flux $-0.05\times$ 1.6 mm flux] in green, Chandra 0.4-6 keV in blue, and VLA 2 cm contours. Inner knots have hard optical spectra and strong X-rays, while outer knots are bright in infrared and radio.

ther below. The heart of an AGN is a supermassive black hole, surrounded by an accretion disk with a hot, ionized corona, which together produce the luminous optical, ultraviolet, and X-ray emission from the galactic nucleus. Photoionized clouds orbiting rapidly near the black hole produce high-excitation broad emission lines, while more distant clouds orbit more slowly and hence radiate lines with narrower profiles. In a minority of AGN, relativistic jets emanate from near the black hole, and extend as far as a Megaparsec from the nucleus.

Here I describe four compelling AGN science questions that can be addressed with a 10-m telescope like the GTC, only a few of the many interesting investigations one could imagine.

2. BLACK HOLE DEMOGRAPHICS, A.K.A. OBSCURED AGN

Over the past two decades we have learned that local AGN are roughly axially symmetric rather than spherically symmetric, meaning that their appearance depends strongly on orientation (Antonucci & Miller 1985; Antonucci 1993; Urry & Padovani 1995). Most local AGN are obscured, so their centers are dim at optical through soft X-ray wavelengths. Furthermore, the spectral shape of the X-ray "background" (actually the superposition of AGN unresolved in early X-ray observations) suggests that the dominant AGN population out to $z \sim 1$ is obscured AGN of moderate luminosity. Thus it is reasonable to expect that at the epoch of peak AGN activity, around $z \sim 2$, most AGN will be missed by optical surveys.

Yet, to understand black hole growth, and the relation of galaxies and black holes during their formation and evolution, we need first to characterize black hole demographics. That is, how many black holes are there, and what are their masses, at each cosmic epoch? Deep X-ray, optical, and infrared images — such as those from the GOODS survey (Dickinson & Giavalisco 2003; Giavalisco et al. 2004) — confirm that most AGN are obscured out to high redshifts. Figure 2 shows a small piece of the GOODS field, with 3 X-ray sources indicated by circles. One of the X-ray sources is unobscured, judging from its X-ray spectrum, and indeed it is bright in the optical (and infrared). The other two, however, have very hard X-ray spectra, likely due to obscuration by gas and dust, and as predicted they are extremely faint and red in the HST image, as expected if the obscuring material absorbs incident optical/UV radiation. At the same time, they are moderately bright in the infrared, just as expected if the obscuring dust and gas is heated and re-radiates the energy.

Detailed analysis of GOODS and other surveys suggests that faint populations ($R > 24$ mag) are dominated by obscured AGN (Treister et al. 2004). The proposed population of faint, obscured sources

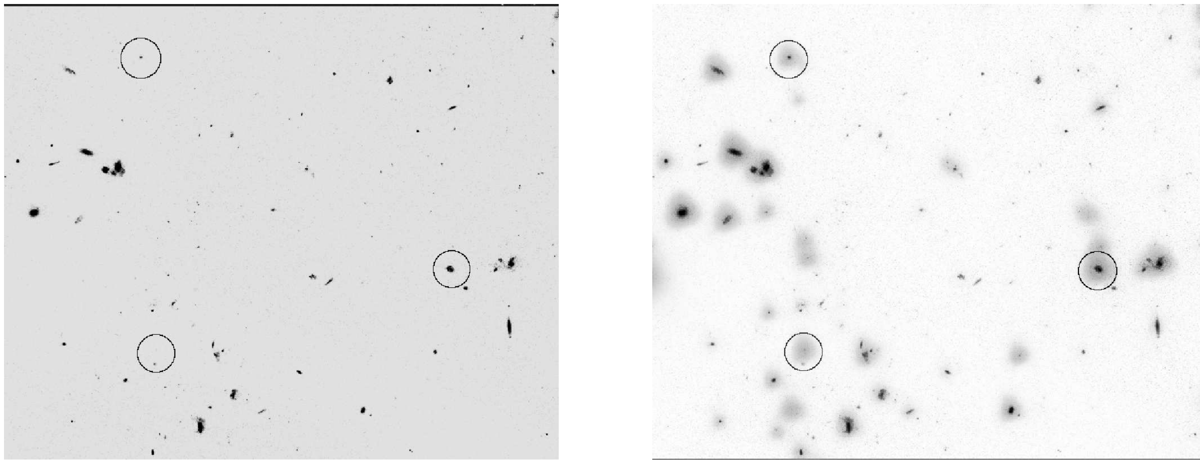

Fig. 2. Small piece (0.3%) of GOODS field showing three X-ray sources (*circles*). *Left:* HST multicolor image. The X-ray source on the right is unabsorbed, according to its X-ray spectrum, and indeed is bright in the optical. The two X-ray sources on the left are heavily absorbed, and very faint and red in the optical. *Right:* HST image with Spitzer 3.6-micron image superimposed. Both optically-faint AGN are bright in the infrared, as expected if the absorbed UV/X-ray light is reradiated by dust.

fits well the X-ray background (Treister et al. 2005) and explains the infrared number counts (Treister et al. 2006). A meta-analysis of the largest, most completely identified, deep multiwavelength surveys shows that obscured AGN are in fact an increasing fraction of the total population (Treister & Urry 2006). Key to this work is obtaining spectroscopic redshifts and characterizing the AGN in terms of their line emission (broad or narrow). Since roughly half the X-ray sources in the deepest surveys are very faint ($R > 24$), 10-m class telescopes are essential to probing black hole demographics.

3. BLACK HOLE MASSES

Once we have located accreting black holes, we would like to know their masses, and ultimately, their mass functions. Black holes masses have been estimated in several ways (Woo & Urry 2002): (1) with dynamical measurements, for example, of gas disks (M87; Harms et al. 1994) or masers (NGC4258; Miyoshi et al. 1993) orbiting the galactic center; (2) from broad emission lines, assuming their orbits are influenced only by gravity, and measuring the orbital radius either from reverberation mapping or from a correlation of reverberation-mapped radius with easier-to-observe optical or UV luminosity (e.g., Vestergaard & Peterson 2006); (3) from the X-ray-observed iron line (e.g., Fabian et al. 2002); (4) from the observed correlation of black hole mass with stellar velocity dispersion (σ), either measuring σ directly or inferring it from galaxy morphology and the fundamental plane relation (O'Dowd et al. 2005, Woo et al. 2005). All of these estimates are uncertain, but the best are probably (2) with reverberation mapping or (4) with direct measurement

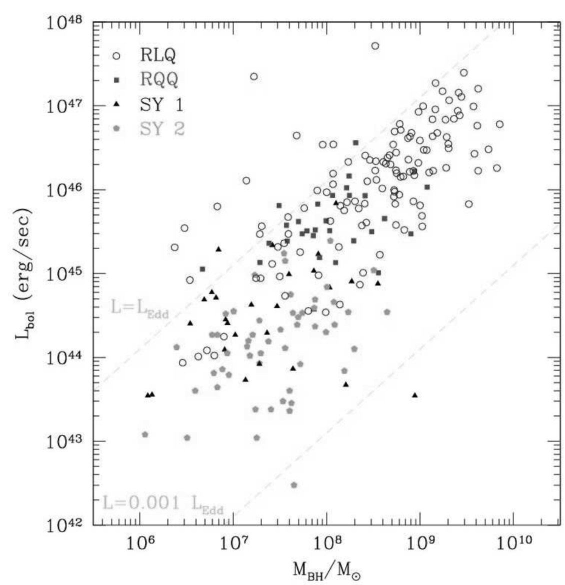

Fig. 3. Bolometric luminosity versus black hole mass for several hundred AGN from various samples (Woo & Urry 2002a), showing little or no significant correlation. At every black hole mass, there is a large range of Eddington luminosity (the broad trend results from L_{Edd} being proportional to black hole mass), with an approximate upper envelope at $\sim 10L/L_{Edd}$. The absence of AGN in the lower right is a selection effect, since objects with under-luminous nuclei are classified as galaxies.

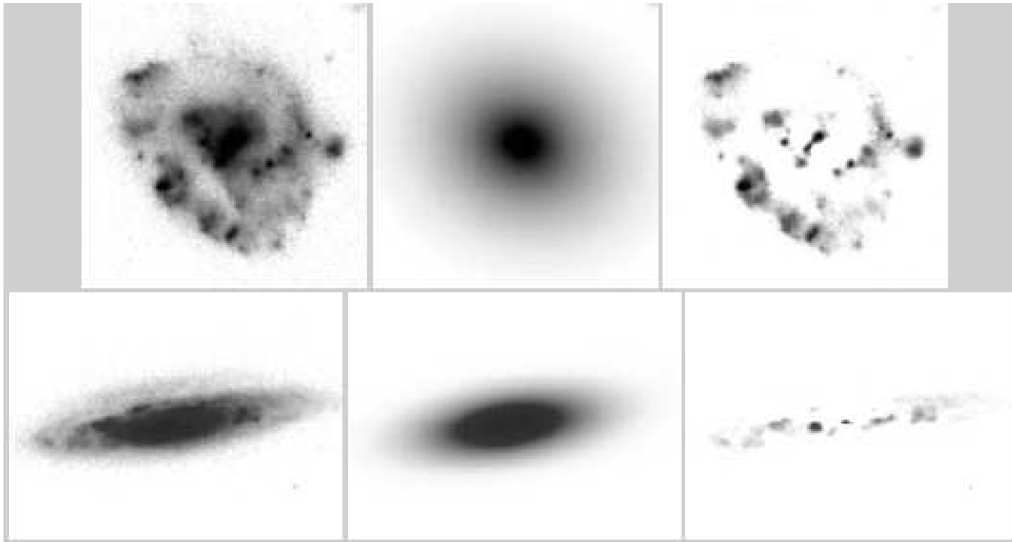

Fig. 4. *(Left panels:)* GOODS images of 2 host galaxies; *(middle:)* Sersic best-fit models; *(right:)* residuals, indicating regions of star formation.

of σ. The former requires intensive monitoring over months to years, and is possible only for a subset of relatively local AGN; the latter is more broadly applicable but requires a 10-m class telescope for all but the nearest AGN. Note that the evolution of the M_{BH}-σ relation with redshift potentially constrains models of galaxy formation and feedback.

Already, even with imperfect mass estimates, some of our preconceptions have been contraindicated. Woo & Urry (2002a) showed there was no clear relation between black hole mass and luminosity, nor between black hole mass and Eddington ratio (see Figure 3); the scatter was commensurate with AGN spanning two or more decades in the Eddington ratio, contrary to the hypothesis that Eddington ratios are higher in high-mass and/or high-luminosity AGN. Woo & Urry (2002b) also refuted the claim that radio-loudness is correlated with black hole mass, or even requires a minimum black hole mass. It is possible that inaccurate mass estimates introduce enough scatter to hide significant correlations, but only better mass estimates will reveal this. At present, whatever weak trends appear in the data are fully explained by the selection effects introduced by flux limits.

4. HOST GALAXIES & GRAND UNIFICATION

The tight correlation between black hole mass and velocity dispersion of the stars in the host galaxy implies a close connection between initial black hole growth and galaxy formation (Kormendy & Gebhardt 2001). This is strongly supported by their similar cosmic evolution from the present day back to $z \sim 2$ or so, by the fact that all bulges host supermassive black holes (Richstone et al. 1998) and that all host galaxies appear perfectly normal (O'Dowd et al. 2005; Woo et al. 2005), and by direct observation of feedback from the AGN onto its surroundings (e.g., Perseus A, Fabian et al. 2000).

Deep optical images with a sensitive, high-resolution imager can potentially reveal the galaxy-black hole connection. For example, Figure 4 shows GOODS images of 2 host galaxies (left panels) fitted with smooth Sersic profiles (middle) that can indicate the amount of gas available. The residuals from the fit (right panel) show evidence of star formation, and multiwavelength colors constrain the stellar ages. Optical imaging also gives information on the AGN environments, including evidence for recent mergers. A high-quality 10-m telescope with adaptive optics and perhaps on-chip seeing correction (as in the One Degree Imager being built by Yale and its WIYN partners) would be ideal for deep imaging of AGN host galaxies.

5. EXTENDED JETS IN RADIO-LOUD AGN

As in the example in Figure 1, some AGN have large-scale, highly collimated jets which flow out from the nucleus at relativistic speeds, and may remain relativistic on the very largest scales. Thousands of radio jets from AGN have been discovered with the VLA (e.g., Bridle & Perley 1984), since even moderately relativistic electrons (with Lorentz factors $\sim 10 - 100$) radiate strongly at radio frequen-

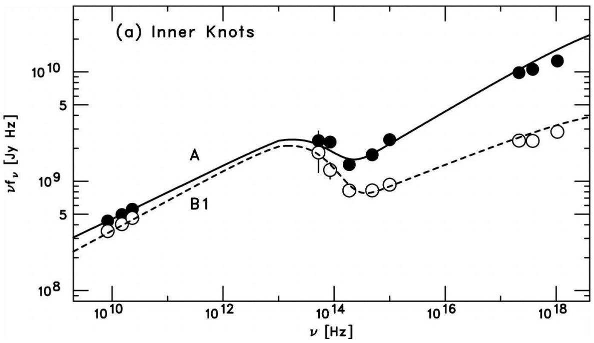

Fig. 5. Broadband spectral energy distributions of inner two, X-ray-bright knots of the 3C273 jet, fitted with 2 power laws. The radio through infrared emission is due to synchrotron radiation. In knot A, half the optical emission comes from the X-ray-emitting component; the similarity of optical and radio polarization therefore argues the X-rays may be synchrotron radiation.

cies via the synchrotron process. Because of its high spatial resolution, HST is capable of detecting optical jets, though only about two dozen have been discovered (all with radio counterparts). In the X-ray, the very first Chandra discovery was of a jet extending hundreds of kiloparsecs in an AGN at $z \sim 0.6$ (Schwartz et al. 2000; Chartas et al. 2000), and a couple of dozen more X-ray jets have since been found (Sambruna et al. 2004; Marshall et al. 2005).

Although we do not fully understand the physical conditions in these jets, even conservative estimates indicate they are extremely powerful. Somehow tremendous amounts of energy are being extracted from the central black hole, and matter is being propagated outwards at nearly the speed of light. Ultimately we would like to understand how this energy is extracted, and indeed, how the black hole environment gives birth to these powerful outflows. First, however, we have to nail down the emission mechanism for the radio through X-ray light from the jet, so that we can accurately infer its power and perhaps its matter content.

Two models have emerged to explain the strong X-rays seen from jets. In some nearby, lower luminosity jets, it appears that radio through X-ray emission is synchrotron radiation from a population of highly relativistic electrons ($\gamma \sim 10^{6-7}$; e.g., M87, Harris et al. 2002). In more distant, powerful jets, a synchrotron mechanism requires instantaneous reacceleration of electrons, implies the jets are very inefficient and far from equipartition of energy between particles and magnetic field, and that their luminosities are extraordinarily large. These considerations led Tavecchio et al. (2000; see also Celotti et al. 2001) to suggest an alternative emission mechanism, whereby electrons in the jet scatter ambient cosmic microwave background radiation to X-ray energies. This model works well if the jet is still moving outward at bulk relativistic speeds, so that the electrons see a Doppler-enhanced CMB field (from the front direction), and scatter it preferentially in the forward direction.

The debate between these two scenarios has raged in the decade since X-rays were first seen from these very extended, powerful jets. Now, with sensitive Spitzer, Hubble, and Chandra observations of 3C273 (Uchiyama et al. 2006, Jester et al. 2006; see Figure 1), we have unprecedented information with which to evaluate emission models. About 9 jet knots are detected with Spitzer along the jet, including the two X-ray-brightest inner knots, whose spectral energy distributions are shown in Figure 5. For the first time we can see that roughly half the optical emission comes from the X-ray spectral component. The radio-through infrared component is well explained by the synchrotron process (which accounts for the other half of the optical emission from the jet), and we know that the radio and optical polarization (on large scales) are similar in degree and angle. This suggests that both radio and optical are produced through the same process, namely synchrotron radiation. In that case, the X-rays must also be synchrotron radiation. This implies extremely efficient particle acceleration that can produce electrons with Lorentz factors of $\gamma \sim 10^8$. One caveat is that the optical polarization is measured for the entire jet, not the inner knots; one should investigate with HST whether the optical polarization is indeed aligned with the radio polarization *in the individual X-ray-emitting knots*.

The bottom line is that sensitive optical and infrared imaging of the jet in 3C273 has given us new insight into the mechanism by which it radiates, and therefore into its energy content. Comparing the kinetic power of the jet to its radiated luminosity can indicate whether the jet is "heavy" (i.e., made of electrons and protons) or "light" (made of electrons and positrons) because in the inner regions, the radiated power must be a small fraction of the total kinetic power or the jet would not propagate further. Applying similar detailed analysis to the knots of other extragalactic jets could give us a sense of the distribution of power in these jets and to their mechanical inertia. Deep, high-resolution optical and infrared imaging (if possible, with a coronagraphic spot) is essential, and thus the GTC would be ideal for this kind of jet study.

6. SUMMARY

I have described four areas in which a large-aperture telescope with powerful instrumentation could contribute significantly to our understanding of AGN. Spectroscopy of faint AGN, especially in the infrared, allows us to probe the demographics of black holes. With very high signal-to-noise ratio spectra, we can measure the stellar velocity dispersions in AGN host galaxies, thus indicating their black hole masses and/or telling us something about the assembly of the host galaxy vis-á-vis the growth of the black hole. With very deep imaging, the GTC could reveal directly star formation in AGN host galaxies, and the relative time scales for galaxy-scale star-formation activity and nuclear black hole accretion. Finally, deep imaging with high spatial resolution, at a wide range of wavelengths from the infrared through optical, promises to illuminate the physical conditions in powerful kiloparsec-scale relativistic jets, and to offer important information for understanding the extraction of energy from the central black hole.

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