AGN properties

- Central black hole
- Accretion disk of infalling gas which radiates - responsible for much of continuum luminosity

Gravity + black hole is an efficient energy source:
~10% of its rest energy (infalling material) is radiated away, of 1% for nuclear burning

- Magnetic fields pulled in too. Close to BH, strong enough to channel twin jets: plasma moves out along spin axis at relativistic speeds

This produces radio emission via synchrotron (and some IR) radiation
Emission lines come from gas clouds further out:
broad line region, then more distant narrow line region.

Just the same as the way radiation pressure in very
massive gets to be important, light from
nucleus of AGN exerts pressure on infalling gas.
If luminosity is too high, nothing can fall in,
so there is a limit on its luminosity.

Assume gas near nucleus is ionized H.
Outward force from Thompson scattering of photons
by electrons: (protons less important since higher mass).

\[
\sigma = \frac{8\pi e^4}{3c^4 M_e^2}
\]

Central source of luminosity L.
Photons have momentum \( \frac{L}{c} \).

Electron of radius \( r \) gets \( \frac{\sigma L}{4\pi r^2 c} \) momentum / sec.
Electrons need to take protons with them as they are pushed out (of coupling before recombination)

Outward force on e+p

- balanced by -

Inward force of gravity

\[
\text{gravity: } \frac{G M (m_e + m_p)}{r^2} \sim \frac{G M m_p}{r^2}
\]

\[
\text{rad. pressure: } \frac{L}{4\pi r^2 c} = \frac{L}{2T} = \frac{L}{\sigma T}
\]

We call the largest possible luminosity that still allows material to accrete the

EDDINGTON LUMINOSITY

\[
L_E = \frac{4\pi G M m_p c}{\sigma T} \sim 3 \times 10^4 \frac{M}{M_\odot} L_\odot
\]
We detect QSOs at redshifts larger than 6. Currently, highest redshifts known for galaxies & QSOs are similar.

QSO activity has been decreasing since then.

What might cause this rise & then fall?
Table 9.1 Densities of normal and active galaxies

<table>
<thead>
<tr>
<th>Type</th>
<th>Locally (Gpc(^{-3}))</th>
<th>At (z \sim 1) (Gpc(^{-3}))</th>
<th>(z \sim 2-3) (Gpc(^{-3}))</th>
<th>(z \sim 4-5) (Gpc(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous galaxies: (L &gt; 0.3L^*) (Fig. 1.16)</td>
<td>7000000</td>
<td>2000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyman break galaxies: (L &gt; 0.3L^*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIRGs: (L_{IR} &gt; 10^{11}L_\odot)</td>
<td>30000</td>
<td>3000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULIRGs: (L_{IR} &gt; 10^{12}L_\odot)</td>
<td>&lt;10000</td>
<td>2000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massive galaxies: (L &gt; (2 - 3)L^*)</td>
<td>400000(^a)</td>
<td>200000(^b)</td>
<td>(10000(^b))</td>
<td></td>
</tr>
<tr>
<td>Seyfert galaxies</td>
<td>100000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio galaxies: (L_r &gt; 2 \times 10^8L_\odot)</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-ray AGN: (L_X &gt; 8 \times 10^{10}L_\odot)</td>
<td>100</td>
<td></td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>(L_X &gt; 2.5 \times 10^9L_\odot)</td>
<td>20000</td>
<td>1000000</td>
<td>30000</td>
<td></td>
</tr>
<tr>
<td>Quasars: (L &gt; 25L^*)</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(L &gt; 100L^*) (Fig. 8.13)</td>
<td>20</td>
<td>600</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Radio-loud quasars: (L_t &gt; 5 \times 10^8L_\odot)</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(L_t &gt; 3 \times 10^{10}L_\odot) (Fig. 8.13)</td>
<td>0.004</td>
<td>0.6</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Densities per comoving Gpc\(^3\) with benchmark cosmology; \(L^* \sim 2 \times 10^{10}L_\odot\) from Figure 1.16. Values in ( ) are known to no better than a factor of 3-5.

\(^b\)Local galaxies from 2dF; \(^b\) ‘red and dead’ galaxies at \(z \sim 1.5\); \(^c\) submillimeter-detected galaxies.

astronomers were puzzled by finding some galaxies with radio-bright compact nuclei and others with huge lobes. Better radio maps revealed tiny central cores at the nuclei of radio galaxies, linked to the outer lobes by bright linear jets that carried energy outward.

The first quasars (for ‘quasi-stellar radio source’) were discovered in the following decade, as ‘radio galaxies with no galaxy’. They appeared pointlike in optical photographs; only their enormous redshifts betrayed that they were not Galactic stars. Rather, they were gigaparsecs distant, and hence extremely luminous. Subsequently ‘radio-quiet’ quasars, called quasi-stellar objects, or QSOs, were found by searching for objects that appeared stellar, but emitted too strongly at infrared or ultraviolet wavelengths relative to their brightness in visible light. Radio-quiet QSOs outnumber radio-loud quasars by at least a factor of 30; both are now believed to be variants of the same type of object, so we use the term ‘quasar’ to include the QSOs. In the 1980s, deep images of nearby quasars showed us that they were in fact the bright nuclei of galaxies, so luminous as to outshine the surrounding stars. Most astronomers now regard quasars as more powerful versions of a Seyfert nucleus. Quasars cover a very wide range in luminosity: Table 9.1 shows that the most powerful are also the rarest.

BL Lac objects are quasars with very weak emission lines; they may be the most extreme form of active nucleus. They are named after their prototype, which was originally thought to be a variable star, and designated BL Lacertae. The light output of these objects can fluctuate enormously within a few days; one was seen to double its brightness within three hours. Both radio and optical emission
resolution of approximately 12 Å and a wavelength coverage of approximately 4000 Å, or the 600 lines mm\(^{-1}\) grating blazed at 10000 Å, which gives a wavelength resolution of approximately 8 Å and a wavelength coverage of approximately 2500 Å. We used the D560 dichroic to obtain simultaneous LRIS-B observations with the 600 lines mm\(^{-1}\) grism blazed at 5000 Å, which for our slit width gives a wavelength resolution of approximately 7 Å and a wavelength coverage of approximately 2000 Å.

Each slit mask was observed for 1.5 hr, broken into three sets of 0.5 hr exposures. Fainter objects were put in more than one mask to provide longer total exposures. Conditions were photometric with seeing \(\sim 0.6-0.8\) FWHM. The objects were stepped along the slits by 2" in each direction, and the sky backgrounds were removed using the median of the images to avoid the difficult and time-consuming problems of flat-fielding LRIS data. Details of the spectroscopic reduction procedures can be found in Cowie et al. (1996).

We successfully obtained redshift identifications for 10 of the 15 hard X-ray sources. Two others were already identified in the literature: source 12 from Ivison et al. (1998) and source 11 from Barger et al. (1999a) and Soucail et al. (1999).

The spectra for the hard X-ray sources (except source 12) are shown in Figure 3, and the redshifts are given in column (10) of Table 1. Strong emission-line features are marked on the plots. We also obtained redshift identifications for eight of the 14 additional soft X-ray sources in the field, and these are given in column (5) of Table 2.

2.4. Radio Observations

A very deep 1.4 GHz map of the A370 field was obtained by Owen et al. (2001), with the National Radio Astronomy Observatory's Very Large Array (VLA). The data are made up of 45 hr in A configuration and 20 hr in B configuration, using the spectral line correlator mode, together with short integration times, to eliminate bandwidth smearing. A large field of view (40' in diameter) was completely imaged. In the region covered by the Chandra results reported here, the effective resolution is 1.6', and the rms...
sion lines, (2) clear signs of [Ne iii] and/or [Ne v] and/or C iv, and (3) no sign of any of the above signatures. The spectra are generally of high quality, and strong high ionization lines are easily seen. We have included four new redshifts in the CDF-N sample (sources 9, 13, 15, and 30) whose spectra will be presented in a forthcoming paper (Barger et al. 2001b). We measured all but three of the redshifts in Table 3 from our own Keck LRIS spectra. The redshifts of the three sources for which we do not have Keck spectra (sources 22, 25, and 26) are taken from the compilation in HOI (the first two were measured by HOI from Hobby-Eberly Telescope spectra, and the last one was mea-

**Fig. 3.—Continued**

**Fig. 4.—**$I$ magnitude vs. 2–7 keV flux for the hard X-ray sources in the A370 (squares), CDF-N (triangles), and SSA 13 (diamonds) fields. Sources with spectroscopic identifications are denoted by filled symbols. The horizontal dotted line at $I = 23.5$ indicates our magnitude division between optically faint and optically bright galaxies; all but seven of the sources brighter than this limit have spectroscopic identifications. The dotted vertical line at $2.4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ is the hard X-ray detection limit for the A370 and the SSA 13 samples. The hard X-ray flux of one of the sources in the A370 field (source 12) is fainter than the hard X-ray detection limit after correcting for cluster magnification.

**Fig. 5.—**Redshift vs. $I$ magnitude for the 45 hard X-ray–selected sources with spectroscopic identifications in the A370 (squares), CDF-N (triangles), and SSA 13 (diamonds) fields and for an $I < 24$ field galaxy sample from the CDF-N, SSA 13, and SSA 22 (small symbols) fields. Superposed are Coleman et al. (1980) evolved tracks for an early-type galaxy (solid line) and an irregular galaxy (dashed line) with $M_I = -22.5$. Sources with broad emission lines are circled.
noise is typically 5.5–6.5 μJy, depending on details of the residual sidelobe distribution from nearby sources; thus, we have adopted 20 μJy as a 3σ upper limit for undetected sources. The radio fluxes were measured at the highest peak within 2″ of each X-ray position; these fluxes are given in column (12) of Table 1 and column (6) of Table 2.

3. COMBINED A370, CDF-N, AND SSA 13 DATA SETS

We hereafter use a combined hard X-ray sample from the A370, CDF-N, and SSA 13 fields. In order to merge the samples, we converted the 2–10 keV fluxes from BOI and the 2–8 keV fluxes from H01 to the 2–7 keV band using Γ = 1.2. The X-ray detection limit for the A370 and SSA 13 samples is 2.4 × 10−15 ergs cm−2 s−1 (2–7 keV), and the detection limit for the CDF-N sample is 5.6 × 10−16 ergs cm−2 s−1 (2–7 keV). For the present work, we have restricted the CDF-N sample to sources with fluxes greater than 10−15 ergs cm−2 s−1 (2–7 keV), which is a 3σ upper limit for undetected sources. The radio fluxes were measured at the highest peak within 2″ of each X-ray position; these fluxes are given in column (12) of Table 1 and column (6) of Table 2.

We include in the table HK′ and B-band magnitudes from, respectively, Barger et al. (1999b) and Barger et al. (2001b). We also include 20 cm data from Richards (2000). The combined sample consists of 69 sources with 2–7 keV fluxes ranging from 10−15 to 2.5 × 10−14 ergs cm−2 s−1.

4. OPTICAL PROPERTIES OF THE COMBINED HARD X-RAY SAMPLES

4.1. Magnitudes

In Figure 4, we plot I magnitude versus 2–7 keV flux for the combined sample. The filled symbols denote sources with spectroscopic identifications; 45 of the 69 sources (65%) have redshift identifications, and all but seven of the sources brighter than I = 23.5 (as indicated by the horizontal line) have redshifts. The three samples are very similar in their distribution of optical magnitudes and redshift identifications.

The median and mean I magnitudes as a function of hard X-ray flux are summarized in Table 4. As has been noted previously (see, e.g., HOI), the data are consistent with a constant optical–to–hard X-ray ratio, although there is a very wide range of optical magnitudes for a given X-ray flux.

In Figure 5, we plot redshift versus I magnitude for the 45 spectroscopically identified sources (large symbols). For comparison, we include on the figure an optically selected I < 24 field galaxy sample (small symbols). We superpose on the figure tracks calculated from the spectral energy distributions of Coleman, Wu, & Weedman (1980) for an early-type galaxy (solid line) and an irregular galaxy (dashed line) in the absence of evolution, both with absolute magnitude $M_r = -22.5$ in the assumed cosmology. BOI noted that the hard X-ray sources predominantly lie in the most optically luminous galaxies, and as Figure 5 illustrates, this is also the case for the combined sample. Brandt et al. (2001a) noted that this property appears to continue to hold to fainter X-ray flux levels ($\sim 3 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$).

We have circled the sources with broad emission lines in their spectra. These sources tend to lie to the left of the evolved galaxy tracks for a given redshift, indicating substantial optical brightening due to the AGN's optical emission.

4.2. Optical Spectral Classification

Following BOI, we classify the optical spectra of the hard X-ray sources into three general categories: (1) broad emission...
The dashed and solid lines are for the models with constant $\alpha$ and $\alpha \propto (1 + z)^{-2}$ respectively. The dotted line shows the star formation rate density occurring in merger-induced bursts in the model with $\alpha \propto (1 + z)^{-2}$. The open symbols are extinction corrected data points read off from fig. 9 of Steidel et al. (1999). These points are derived from the data of Lilly et al. (1996) [circles], Connolly et al. (1997) [squares], Madau et al. (1996) [triangles] and Steidel et al. (1999) [crosses]. The model in which $\alpha$ evolves with redshift as $(1 + z)^{-2}$, the percentage of stars formed in merger-induced bursts increases from less than 10 per cent at $z = 0$ to 50 per cent at $z = 2.5$. By redshift 4, two-thirds of the total star formation occurs in the burst mode. In the model with constant $\alpha$, the fraction of stars formed in bursts increases much less, from $\sim 10$ per cent at $z = 0$ to 25 per cent at high redshift. As will be demonstrated in the next sections, the constant $\alpha$ model is unable to fit the observed increase in the quasar space densities at high redshift.

Fig. 3 compares the predicted evolution of the mean mass density in the form of cold galactic gas in the models compared with the values derived from surveys of damped Ly$\alpha$ systems by Storrie-Lombardi et al. (1996). As can be seen, the model with $\alpha \propto (1 + z)^{-2}$ agrees well with the data, but the model with constant $\alpha$ severely underpredicts the mass density of cold gas at high redshifts. Note that the error bars on the data points in Fig. 2 are large, and that taking into account the effects of dust extinction would tend to move the points upwards (Pei & Fall 1995). The model in which $\alpha \propto (1 + z)^{-2}$ thus cannot be excluded. As we discuss in Section 5 below, this model leads to the strongest evolution in the quasar space densities.

4 THE GROWTH OF BLACK HOLES AND THE BULGE LUMINOSITY – BLACK HOLE MASS RELATION

In our models, supermassive black holes grow by merging and the accretion of gas during major mergers of galaxies. We assume that when any merger between two galaxies takes place, the two pre-existing black holes in the progenitor galaxies coalesce instantaneously. In major mergers, some fraction of the cold gas in the progenitor galaxies is also accreted on to the new black hole. The rest is converted into stars in a burst of duration $10^8$ yr. As discussed in the previous section, the cold gas fractions of galaxies increase strongly with redshift. In hierarchical cosmologies, low-mass bulges form at higher redshift than high-mass bulges. To obtain the observed linear relation between black hole mass and bulge mass, the fraction of gas accreted by the black hole must be smaller for low-mass galaxies, which seems reasonable because gas is more easily expelled from shallower potential wells (equation 1). We adopt a prescription in which the ratio of accreted mass to total available cold gas mass scales with halo circular velocity in the same way as the mass of stars formed per unit mass of cooling gas. For the parameters of our model, this may be written as

$$M_{\text{acc}} = \frac{f_{\text{BH}} M_{\text{cold}}}{1 + (280 \, \text{km s}^{-1} / V_c)^2}. \quad (2)$$

$f_{\text{BH}}$ is a free parameter, which we set by matching to the observed relation between bulge luminosity and black hole mass of Magorrian et al. (1998) at a fiducial bulge luminosity $M_V = -19$. We obtain $f_{\text{BH}} = 0.03$ for the model with $\alpha \propto (1 + z)^{-2}$, $f_{\text{BH}} = 0.04$ for the model with $\alpha \propto (1 + z)^{-2}$ and $f_{\text{BH}} = 0.095$ for the constant $\alpha$ model, a value which is uncomfortably large.

There are no doubt physical processes other than major mergers that contribute to the growth of supermassive black holes (for a more detailed discussion, see Haehnelt et al. 1998). For example, we have neglected the accretion of gas during minor mergers when a small satellite galaxy falls into a much larger galaxy (Hernquist & Mihos 1995). We have also neglected the accretion of gas from the surrounding hot halo (Fabian & Rees 1995; Nulsen & Fabian 1999). It has been suggested that this may occur in the form of advection-dominated accretion flows (Narayan & Yi 1995) and may produce the hard X-ray background (Di Matteo & Fabian 1997). Finally, we have also neglected bar-driven accretion...
QSO duty cycle

Bright QSOs (even Seyfert galaxies) are much less common than massive galaxies.

We know that all massive galaxies contain a central supermassive black hole.

Black holes have an AGN phase when they are accreting & luminous .... how common?

Chandra X-ray observations \( \Rightarrow \) X-ray LF of galaxies (match to optical sources for redshift)

Comparison with optical LF of massive galaxies \( \Rightarrow \) that redshift

\( \Rightarrow \) \( \approx \) 4% of \( L^* \) and greater galaxies are X-ray luminous at any time

\( \Rightarrow \) average duration of AGN phase of supermassive BH (ie accretion) is \( \approx \) 0.5 Gyr.