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Accessibility
The X-Ray Properties of 2MASS Red Active Galactic Nuclei

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ABSTRACT

The Two Micron All Sky Survey is finding previously unidentified, luminous, red, active galactic nuclei (AGNs). This new sample has a space density similar to, or greater than, previously known AGNs, suggesting that a large fraction of the overall population has been missed. Chandra observations of a well-defined subset of these objects reveal that all are X-ray–faint, with the reddest sources being the faintest in X-rays. The X-ray hardness ratios cover a wide range, generally indicating $N_H \sim 10^{21} - 10^{23}$ cm$^{-2}$, but the softest sources show no spectral evidence for intrinsic absorption. These characteristics suggest that a mix of absorbed, direct emission and unabsorbed, scattered, and/or extended emission contributes to the X-ray flux, although we cannot rule out the possibility that they are intrinsically X-ray–weak. This population of X-ray–faint, predominantly broad-line objects could provide the missing population of X-ray–absorbed AGNs required by current models of the cosmic X-ray background. The existence of AGNs that display both broad emission lines and absorbed X-rays has important implications for unification schemes and emphasizes the need for care in assigning classifications to individual AGNs.

Subject headings: quasars: general — surveys — X-rays: galaxies

1. INTRODUCTION

The realization that obscuration plays a critical role in the classification of active galactic nuclei (AGNs) inspired a fundamental change in our understanding of the phenomenon. Not only does the “unified scheme,” in which narrow emission line (type 2) AGNs are interpreted as edge-on broad emission line (type 1) AGNs, provide a basis for new observations and theoretical models, but it also reveals that many AGNs may be nearly invisible in UV-excess surveys (e.g., Webster et al. 1995; Masci, Drinkwater, & Webster 1999). This expanded idea of what comprises an AGN means that their current number density may be significantly underestimated (e.g., Sanders & Mirabel 1996). Ramifications include revisions of the fraction and types of galaxies that harbor an active nucleus, the energy density of ionizing flux in the young universe, and the nature of the X-ray and far-IR backgrounds.

Although IRAS provided the first significant sample of extragalactic objects in which the bulk of the luminosity emerges as reprocessed radiation in the IR (Soifer et al. 1984), its sensitivity was sufficient to catalog only the most nearby and/or luminous AGNs. The Two Micron All Sky Survey (2MASS) is yielding a much deeper catalog of near-IR–selected AGNs (Cutri et al. 2001) by selecting sources with $J - K_s > 2$ from the high Galactic latitude 2MASS Point Source Catalog. Spectroscopic follow-up of red candidates reveals $\sim 75\%$ are previously unidentified emission-line AGNs, with $\sim 80\%$ of these showing broad optical emission lines (type 1: Seyfert 1 galaxies and quasi-stellar objects [QSOs]); the remainder being narrow-line objects (type 2: Seyfert 2 galaxies, type 2 QSOs, and LINERS; Cutri et al. 2001). They span a redshift range of $0.1 < z < 2.3$ with a median value of $0.25$. The inferred surface density is $\sim 0.5$ deg$^{-2}$ brighter than $K_s = 14.5$ mag, higher than that of optically selected AGNs at the same IR magnitudes and indicating that 2MASS will reveal greater than 25,000 such objects over the sky. The objects have unusually high optical polarization levels, with $\sim 10\%$ showing $P > 3\%$ indicating a significant contribution from scattered light (Smith et al. 2001).

ROSAT found that, while known AGNs dominate the soft (0.1–2.0 keV) cosmic X-ray background (CXRB; Lehmann et al. 2000), an additional population of heavily absorbed AGNs would be required to account for the harder, high-energy spectrum (Comastri et al. 1995). To match both the CXRB spectrum and the observed hard X-ray number counts of pre-Chandra surveys (Fiore et al. 2001), the X-ray–absorbed AGN population is estimated to outnumber unabsorbed AGNs by $\sim 4:1$ and perhaps to increase with $z$ (Gilli, Salvati, & Hasinger 2001; Comastri et al. 2001). Although the ratio of type 2 to type 1 AGNs in the local universe is consistent with this: $\sim 2:4$ (Maiolino & Rieke 1995; Huchra & Burg 1992), a dominant population of X-ray–absorbed AGNs at $z \gtrsim 0.1$ has yet to be found. Possible identifications include advection dominated accretion flow galaxies (Di Matteo et al. 1999) and narrow emission line X-ray galaxies with flat/absorbed X-ray spectra, luminous IR galaxies (Risaliti et al. 1999), and a subset of broad-line AGNs that are X-ray absorbed.

The Chandra X-Ray Observatory (Weisskopf et al. 2000) and XMM-Newton (Jansen et al. 2001), with their faint flux limits and broad energy sensitivity ($\sim 0.5–10$ keV), are finding objects in sufficient numbers to explain 60%–80% of the CXRB, including a significant number of hard spectrum sources. These correspond to both optically faint objects and bright, nearby, but otherwise normal elliptical galaxies (Hornschemeir et al. 2000; Barger et al. 2001; Giacconi et al. 2001), as well as more traditional, broad-line AGNs. Near-IR observations of the galaxies reveal featureless, red continua ($1.5 < J - K_s < 2.5$) that, combined with their optical colors, are consistent with the moderate amounts of absorption required to match the CXRB (Compton-thin; equivalent neutral hydrogen column density $N_H < 10^{24}$ cm$^{-2}$; Crawford et al. 2001; Barger et al. 2001). Thus, evidence is mounting that absorbed AGNs are indeed important contributors to the CXRB.

The area covered by the deepest Chandra surveys is small
(~0.16 deg²), resulting in large statistical uncertainties, particularly at low z. Given the high surface density and the similarities of the new population of 2MASS AGNs to the smaller Chandra sample, a census of the X-ray properties of the 2MASS AGNs will likely be an essential ingredient in their understanding and will yield an estimate of whether this previously missed population is sufficient, alone, to explain the shortfall in the CXRB.

2. OBSERVATIONS

We are surveying a well-defined, flux-limited, and color-selected subset of 26 2MASS AGNs using the Advanced CCD Imaging Spectrometer array (Nousek et al. 1998) on Chandra. The subset was selected to have B−Ks > 4.3 and Ks < 13.8, including the brightest and reddest objects, but covering sufficient parameter space to be representative of the new population: 0 < z < 0.4 and 0 < P(%) < 9.3 (Smith et al. 2001). Included are six narrow-line (type 2) AGNs and 20 with broad optical emission line components (types 1, 1.5, and 1.8). Because the observed Ks-band–to–X-ray slopes for AGNs span a wide range4 (1.1 ≤ αKs,X ≤ 2; Elvis et al. 1994; Lawrence et al. 1997), the X-ray flux expected from the 2MASS sample is uncertain by a factor of ~800, even if they have properties similar to “normal” AGNs. Observing times ranging from 1 to 4.5 ks were selected to acquire at least 5 counts at the faintest end of this range.

X-ray counts and hardness ratios (HRs) for the 23 targets observed to date are summarized in Table 1. Virtually all source counts are contained in the 279 (5.75 pixel) radius extraction aperture that was centered on the source. Background counts were estimated from an annulus with inner and outer radii of 10 and 30 pixels, respectively. Four targets are undetected.

3. SPECTRAL ENERGY DISTRIBUTIONS

A comparison of the Ks-band–to–1 keV flux density ratios (the latter computed assuming a normal AGN X-ray spectrum; N0 = 3 × 10²⁰ cm⁻² and αKs = 1.0, where Fα ∝ να) with those of low-redshift, broad-line AGNs (Fig. 1) demonstrates

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| Name (2MASS) | Date         | Exposure | Counts | HR | J−Ks  |
|--------------|--------------|----------|--------|----|-------|
| 000703+1554  | 2001 Jan 16  | 3533     | 99     | 0.5 ± 0.1 | 2.129 |
| 005055+2933  | 2001 Jan 25  | 3644     | 120    | 0.1 ± 0.1 | 2.114 |
| 010835+2148  | 2001 Jan 26  | 3100     | 10     | 0.2 ± 0.4 | 2.754 |
| 012031+2003  | 2001 Jan 26  | 1538     | <5     | ... | 3.851 |
| 015721+1712  | 2001 Jan 26  | 2700     | 135    | −0.2 ± 0.4 | 2.702 |
| 022150+1377  | 2001 Aug 03  | 3483     | 79     | −0.2 ± 0.2 | 2.376 |
| 023430+2438  | 2001 Jan 25  | 4138     | 11     | −0.1 ± 0.4 | 2.196 |
| 034857+1255  | 2001 Jan 25  | 4847     | <5     | ... | 3.296 |
| 091848+2117  | 2001 Feb 18  | 2160     | 154    | −0.6 ± 0.1 | 2.274 |
| 095504+1705  | 2001 Jan 29  | 4132     | 62     | 0.4 ± 0.2 | 2.025 |
| 102722+1152  | 2001 Oct 16  | 3249     | 35     | 0.2 ± 0.2 | 2.057 |
| 105144+3539  | 2001 Feb 13  | 4436     | 473    | −0.2 ± 0.1 | 2.105 |
| 125807+2329  | 2001 Jul 30  | 3140     | <5     | ... | 2.066 |
| 130005+1632  | 2001 Jul 30  | 887      | 127    | 0.2 ± 0.1 | 2.199 |
| 130700+2338  | 2001 May 27  | 3500     | 7      | ... | 3.342 |
| 140251+2631  | 2001 Jul 04  | 1730     | 340    | −0.6 ± 0.1 | 2.114 |
| 145331+1353  | 2001 Jun 01  | 3156     | <5     | ... | 2.298 |
| 150113+2329  | 2001 Jul 26  | 3368     | 58     | −0.3 ± 0.2 | 2.412 |
| 151653+1900  | 2001 Apr 27  | 1132     | 23     | 0.1 ± 0.3 | 2.121 |
| 163700+2221  | 2001 Jun 13  | 4371     | 163    | −0.2 ± 0.1 | 2.095 |
| 165939+1834  | 2001 Jul 13  | 2406     | 24     | 0.6 ± 0.3 | 2.167 |
| 222554+1958  | 2000 Oct 02  | 3934     | 80     | 0.5 ± 0.2 | 2.148 |
| 234449+1221  | 2001 Jan 16  | 1937     | 244    | −0.4 ± 0.1 | 2.073 |
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4 Seyfert 2 galaxies and broad absorption line (BAL) QSOs lie at the extreme X-ray faint end of this range.

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**Fig. 1.**—Observed X-ray–to–Ks flux ratio (1 keV X-ray flux assuming a normal AGN X-ray spectrum: αKs = 1.0, N0 = 3 × 10²⁰ cm⁻²) as a function of redshift for the 2MASS AGNs (circles) compared with the same ratio for low-redshift, broad-line AGNs (crosses; Elvis et al. 1994). Upper limits are indicated by triangles, and the reddest sources (J−Ks > 2.5) are indicated by an enclosed square. The filled squares show the BAL QSOs IRAS 07598+6508 and FIRST J0840+3663 (Green et al. 2001; Low et al. 1989; 2MASS).
the general weakness of X-ray emission from the 2MASS QSOs, placing them in the range measured for BAL QSOs and Seyfert 2 galaxies (Fig. 1). We also find that the objects with the reddest colors ($J-K_s > 2.5$) are the weakest X-ray sources (>99% significance; see Fig. 1). This suggests either an underlying, nonthermal power law with a range of slopes dominating the near-IR and X-ray spectral regions (Carleton et al. 1987; Brissenden 1989) or correlated absorption in the near-IR and X-ray regions. The latter would predict hard X-ray spectra for these sources.

The low signal-to-noise ratio (S/N) of most of the observations does not permit direct measurements of the X-ray spectral slope and absorption. Instead, we evaluate the X-ray HR (Table 1). A normal AGN X-ray spectrum with little absorption ($\alpha_e \sim 1.0$) yields a Chandra HR of $\sim 0.7$ in the bands used here. The 2MASS sample covers the range of $-0.6 < HR < +0.6$, consistent with $N_H \sim 10^{21} - 10^{23} \text{ cm}^{-2}$ for most sources. One 2MASS AGN of type 1.5 and one of type 1 are consistent with no absorption above the Galactic column ($HR < -0.5$). These results are shown in Figure 2, in which it is seen that the 2MASS sources tend to fall intermediate between values derived for the optically selected Palomar-Green (PG) QSOs (Laor et al. 1997) and the Seyfert 2 galaxies (Risaliti, Maiolino, & Salvati 1999).

There is no relation between HR and $J-K_s$, i.e.; while X-ray fainter, the reddest objects do not have the hardest spectra, as might be expected in a simple optical and X-ray absorption scenario. Neither X-ray flux nor HR appears to be related to AGN class or to optical polarization level. While these estimates of $N_H$ are instructive, HRs are, at best, a crude measure of the true $N_H$. The X-ray spectra of AGNs often contain a number of components that modify the power-law continuum emission believed to originate in the central AGN. In addition to the cold-absorbing material we assumed above, these include partial covering of the source, an ionized absorber, extended emission, and scattering/reflection by neutral and/or ionized material. For example, the spectrum of NGC 1068 is a mix of neutral and ionized reflection of an otherwise invisible nuclear continuum (Matt et al. 1997), so that the observed HR is decoupled from the intrinsic cold absorber. Without spectral deconvolution of high S/N data, it is not possible to distinguish between the various possibilities. Correction of the X-ray flux for absorption as suggested by the HRs moves only about half of the 2MASS sample into the area occupied by the Elvis et al. (1994) AGNs in Figure 1, suggesting that complex spectra result in excess soft emission in many sources. However, we cannot rule out the alternate possibility that the X-ray emission of at least some 2MASS AGNs is dominated by a power law that is intrinsically faint and hard.

### 4. OPTICAL AND X-RAY–ABSORBING MATERIAL

Assuming that dust extinction is responsible for the red colors of 2MASS AGNs and that absorption by associated gas is responsible for the hardness of the X-ray spectra, we can compare the equivalent column densities on a case-by-case basis. We assume that the median, rest-frame $J-K_s$ for an AGN is 2.04 (Elvis et al. 1994) and determine $E(J-K_s)$ from the observed $J-K_s$ color. Comparison between this and the X-ray–derived $N_H$ shows that the ratio $E(J-K_s)/N_H$ is reduced by a factor of a few to $\sim 100$ compared with the Galactic value of $0.98 \times 10^{-22} \text{ cm}^2 \text{ mag}$, the latter being computed from the ROSAT dust extinction versus gas absorption relation (Seward 1999) and the extinction curve from Mathis (1999). A similar result was reported for optical $[E(B-V)]$ versus X-ray extinction in AGNs by Maiolino et al. (2001), who suggest an explanation in terms of anomalous dust, dominated by large grains, that absorbs with little spectral reddening. Other possibilities include different lines of sight to the X-ray and IR continuum emitting regions such that much of the X-ray–absorbing material does not cover the optical/IR source (Risaliti et al. 2000), or absorbing material that is hotter than the dust sublimation temperature and so is largely dust-free and/or physically decoupled from the dust (Granato, Danese, & Franceschini 1997; Risaliti, Elvis, & Nicolaci 2001). Optical spectropolarimetry to study the scattering material combined with improved constraints on the X-ray–absorbing column density for a significant number of these AGNs will allow us to distinguish between these various possibilities.

A similar comparison of the reddening indicated by $B-K_s$ color with that from the near-IR shows good agreement in most cases, particularly given the large uncertainties associated with the $B$ magnitudes from the USNO-A2.0 catalog (Monet et al. 1998). A small subset of the 2MASS AGNs show less optical than near-IR reddening, probably because of host galaxy and/or scattered nuclear light contributing to the optical flux. Although there is no clear correlation between the discrepancy and the optical polarization level, the source with the largest discrepancy ($\sim 3.7 \text{ mag}$) has $P = 6\%$. Alternatively, additional IR emission from hot dust could increase the light at $K_s$.

### 5. RED AGN AND THE CXRB

Current CXRB models require a population of X-ray–absorbed AGNs that has yet to be found beyond the local universe. It is not essential that these objects be classified as AGNs at other wavelengths, but the various source populations considered to date, including luminous IR galaxies, Seyfert 2 galaxies, type 2 QSOs, LINERs, normal galaxies, etc., are insufficient to account for the measured surface brightness.

The new population of predominantly type 1 AGNs being discovered in the 2MASS AGN survey at least doubles the density of broad-line objects at $z \leq 0.5$. The bias toward low-$z$ objects inherent in the 2MASS color-selection process implies that such a population is also present at high $z$. If so, their
numbers combined with the hardness of their X-ray spectra imply that the predominantly type 1 AGNs can account for most of the missing CXRB population, as opposed to type 2 AGNs or other heavily obscured objects. However, the high-z counterparts will need to be found by other means such as, e.g., looking for red sources in the longer wavelength SIRTF bands. More distant absorbed, type 1 AGNs have been found, but they are not common and are usually identified as radio-loud quasars (Reeves & Turner 2000; Gregg et al. 2001).

6. THE NATURE OF X-RAY–ABSORBED, BROAD-LINE AGNs

The presence in this sample of type 1 AGNs with absorbed X-ray spectra suggests that a simple unification scenario in which edge-on AGNs exhibit narrow optical lines with the broad lines and X-ray emission being strongly absorbed, while face-on counterparts are unobscured in both emission lines and X-rays, is too simplistic. It also emphasizes that classifications may not apply across the wave band in which they were made.

The combination of X-ray absorption, red near-IR continuum, polarized optical continuum, and broad lines in the majority of 2MASS AGNs suggests that they are viewed at an intermediate line of sight with respect to dusty, nuclear material (e.g., torus/disk/wind), as has been proposed for the similarly polarized BAL QSOs. The X-ray–absorbing medium must be mostly dust free, perhaps being largely inside the sublimation radius, and patchy, resulting in the partial covering of the broad emission line region. The emission lines and/or optical continuum may include a scattered component, perhaps from absorbing material on the farside of the engine, as has been suggested for BAL QSOs (Schmidt & Hines 1999; Ogle 1999 and references therein). It seems likely that a scenario similar to the accretion disk plus outflowing wind proffered to explain various aspects of AGNs (e.g., Weymann et al. 1991; Voit et al. 1993; Murray & Chiang 1995; Ogle 1999; Elvis 2000) could be invoked for these objects as well. If so, it is likely that many of the 2MASS AGNs will show broad absorption lines in their UV spectra. Their X-ray weakness, along with that of optical type 2’s and BAL QSOs, also suggests that highly obscured objects may go undetected even in the X-rays, so that weak or nondetected X-ray emission does not rule out the presence of an active nucleus. However, a more detailed study of their optical and X-ray emission is needed before applying such a scenario in detail.

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