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A SPECTACULAR POST-STARBURST QUASAR

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ABSTRACT

We report the discovery of a spectacular "post-starburst quasar" UN J1025−0040 ($B = 19$; $z = 0.634$). The optical spectrum is a chimera, displaying the broad Mg II λ2800 emission line and strong blue continuum characteristic of quasars, but is dominated in the red by a large Balmer jump and prominent high-order Balmer absorption lines indicative of a substantial young stellar population at similar redshift. Stellar synthesis population models show that the stellar component is consistent with a 400 Myr old instantaneous starburst with a mass of $\lesssim 10^{11}$ $M_\odot$. A deep, K_s-band image taken in $\sim 0.5''$ seeing shows a point source surrounded by asymmetric extended fuzz. Approximately 70% of the light is unresolved, the majority of which is expected to be emitted by the starburst. While starbursts and galaxy interactions have been previously associated with quasars, no quasar ever before has been seen with such an extremely luminous young stellar population.

Subject headings: galaxies: evolution – galaxies: interactions – galaxies: starburst – quasars: emission lines – quasars: general

1. INTRODUCTION

Is there a connection between starbursts and quasar activity? There is circumstantial evidence to suggest so. 3C 48 is surrounded by nebulosity that shows the high-order Balmer absorption lines characteristic of A-type stars (Boroson & Oke 1984; Stockton & Ridgeway 1991). PG 1700+518 shows a nearby starburst ring (Hines et al. 1999) with the spectrum of a 10^8-year-old starburst (Stockton, Canalizo, & Close 1998). Near-IR and CO mapping reveals a massive ($\sim 10^{10} M_\odot$) circumnuclear starburst ring in I Zw 1 (Schinnerer et al. 1998). The binary quasar member FIRST J164311.3+315618B shows a starburst host galaxy spectrum (Brotherton et al. 1999).

In addition to these individual objects, *samples* of active galactic nuclei (AGNs) are showing evidence for starbursts. Images of quasars taken with the *Hubble Space Telescope* show "chains of emission nebulae" and "near-nuclear emission knots" (e.g., Bahcall et al. 1997). Seyfert 2 and radio galaxies have significant populations of $\sim$100 Myr old stars (e.g., Schmitt, Storchi-Bergmann, & Cid Fernandes 1999). Half of the ultraluminous infrared galaxies (ULIRGs) contain simultaneously an AGN and recent (10-100 Myr) starburst activity in a 1-2 kpc circumnuclear ring (Genzel et al. 1998).

The advent of *IRAS* provided evidence for an evolutionary link between starbursts and AGNs. The ULIRGs (L_{IR} $> 10^{12} L_\odot$) are strongly interacting merger systems with copious molecular gas [$(0.5-2)\times 10^{10} M_\odot$] and dust heated by both starburst and AGN power sources. The ULIRG space density is sufficient to form the quasar parent population. These facts led Sanders et al. (1988) to hypothesize that ULIRGs represent the initial dust-enshrouded stage of a quasar. Supporting this hypothesis is the similarity in the evolution of the quasar luminosity density and the star formation rate (e.g., Boyle & Terlevich 1998; Percival & Miller 1999). Another clue is that supermassive black holes appear ubiquitously in local massive galaxies, which may be out-of-fuel quasars (e.g., Magorrian et al. 1998). AGN activity may therefore reflect a fundamental stage of galaxy evolution.

We report here the discovery of a post-starburst quasar. The extreme properties of this system may help shed light on the elusive AGN-starburst connection. We adopt $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

2. OBSERVATIONS

2.1. *Selection and Spectroscopy*

We identified UN J1025−0040 as a quasar candidate in the UVX-NVSS (UN) catalog: entries include candidates from the ultraviolet excess (UVX) AAT-2dF quasar survey (Smith et al. 1996) within 10″ of a radio source from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). UN J1025−0040 was identified as a stellar optical source, with $B_j = 19.34, U - B_j = -0.28$, and $B_j - R = 0.93$. The optical position is α=10h25m00.78s, $\delta=-00^\circ 40' 44\overset{''}{.}9$ (J2000), 6″ from an unresolved NVSS source with a 20 cm flux density of 9.2±0.6 mJy. A new map from the FIRST

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survey (Becker, White, & Helfand 1995) shows a 20 cm source with $\sim$ 3 mJy and a separation of less than an arcsecond from the optical counterpart (R. Becker, priv. comm.). The difference in positions and flux densities of the two radio surveys are consistent with the presence of extended emission "resolved out" at high resolution.

We obtained 4 minute Keck "snapshot" spectra of UN J1025−0040 and other quasar candidates from the equatorial (+2.5° to −2.5°) UVX-NVSS catalog with $18.25 < B_j \leq 20.00$ and right ascensions from 10–13 hours (see Brotherton et al. 1998). Observations were conducted with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on 1998 February 9 (UT) with the slit oriented north-south. The 300 line mm^{-1} grating blazed at 5000 Å with a 1″ slit gave an effective resolution $\leq$ 10 Å covering 4000 Å to 9000 Å. We employed standard data reduction techniques within the NOAO IRAF package.

We also obtained spectropolarimetry using LRIS at the Keck II telescope on 1998 March 6 (UT). The 60 minute observation was broken into four 15 minute exposures, one for each waveplate position (0°, 45°, 22.5°, 67.5°). The 600 line mm^{-1} grating blazed at 5000 Å with a 1″ slit gave an effective resolution $\leq$ 5 Å covering 4300 Å to 6800 Å. We used standard reduction techniques inside the IRAF NOAO package and the procedures of Miller, Robinson, & Goodrich (1988) for calculating Stokes parameters and errors. Binning the data (in q and u) from 4500-6500 Å yields a polarization of $p = 1.28 \pm 0.05\%, \theta = 62.5° \pm 1.2°$. We have sufficient S/N ratio to distinguish between "blue" and "red" polarizations: binning from 4400-5400 Å (below the redshifted Balmer jump) yields $p = 1.0 \pm 0.1\%, \theta = 61.3° \pm 2.2°$, while binning from 6200-6700 Å (above the redshifted Balmer jump) yields $p = 1.6 \pm 0.1\%, \theta = 66.1° \pm 1.6°$.

The Galactic reddening in the direction of UN J1025-0040 is $E(B-V) = 0.057$ mag (Schlegel, Finkbeiner, & Davis 1998). The *maximum* expected polarization from interstellar polarization is $9 \times E(B-V)\%$ (Serkowski, Mathewson, & Ford 1975), or 0.5%. The polarization in UN J1025-0040 is therefore intrinsic.

Figure 1 (top) shows the total-light spectrum of UN J1025−0040.

2.2. *Near-Infrared Imaging*

We imaged UN J1025−0040 in K_s using NIRC (Matthews & Soifer 1994) at the Keck I Telescope on 18 April 1998 when conditions were clear with $\sim$0.″5 seeing. The total on-source exposure time was 1920 s. After bias subtraction, linearization, and flatfielding (using sky flats), the data were sky–subtracted, registered, and summed using DIMSUM[1]. Subsequent photometry was flux calibrated via observations of UKIRT faint standards (Casali & Hawarden 1992), which, after a suitable transformation, yields magnitudes on the Caltech system. The image (Fig. 2) shows a strong unresolved source surrounded by asymmetric extended fuzz with a feature suggestive of a dust lane, and a companion ($K_s = 20.7$, 4.″5 to the SSW).

3. SPECTRAL ANALYSIS: STARBURST AND QUASAR

We explored the stellar synthesis population models of Bruzual & Charlot (1999) in order to interpret the "A-star" spectrum of UN J1025−0040. The size of the Balmer jump, even diluted by a quasar continuum, argues for a population several times $> 10^8$ years old. The fact that there is a Balmer jump rather than a 4000 Å break suggests that the age is less than $\sim$0.5 Gyr. A solar metallicity, Salpeter initial mass function (0.1 to 125 $M_\odot$), 400 Myr old instantaneous starburst (ISB) model reproduces the observed features rather well (Fig. 1). The mass of the starburst, as determined by the model mass and its scaling to the observed spectrum, is large: 7×10^{10} $M_\odot$.

Although this very simple model matches the observed features rather well, there are additional complexities to keep in mind. If the metalicity is much higher than solar, a younger ($\gtrsim$350 Myr) stellar population can reproduce the spectrum, while a lower metalicity allows for an older population ($\lesssim$ 450 Myr). The modeling at these epochs is not very sensitive to the choice of initial mass function. A second population, such as that of the old underlying host galaxy, probably contributes at some level, but is not yet required in the modeling. Also not yet required is the invocation of dust reddening, although it is possible that some is present in one or more components. These effects can raise or lower the mass estimate by factors of a few.

While the Balmer absorption lines and [O III] $\lambda\lambda$4959,5007 have the same redshift of $z = 0.634$, the broad (FWHM = 5500±500 km s^{-1}) Mg II λ2800 is at $z = 0.627$. After subtracting off the ISB model from the low-resolution spectrum (bottom panel Fig. 1), broad Hβ is revealed, also with a peak at $z = 0.627$. Low-ionization broad lines blueshifted by $\sim$1000 km s^{-1} are not unprecedented (e.g., Marziani et al. 1996). Also worth noting is that the line intensity ratio Mg II λ2800/H$\beta \approx 5$, while values of 0.5-2.5 are more typical (Grandi & Phillips 1979). Otherwise the quasar spectrum appears typical, if slightly bluer than average.

4. IMAGE ANALYSIS: POINT SOURCE AND "FUZZ"

We have performed a one-dimensional profile analysis of our image in order to separate the unresolved nucleus from the surrounding fuzz. We used the ellipse fitting procedure in IRAF STSDAS to generate a radial intensity profile of UN J1025-0040. An appropriate star with a similar count rate to UN J1025-0040 was used to generate a PSF profile. The surface brightness profile limit is about 22 mag arcsec^{-2}. We subtracted different amounts of this PSF from the UN J1025-0040 profile, trying to find values for which the residual would be linear with r (disk fit) or $r^{1/4}$ (De Vaucouleurs fit). For both fits, 70% of the normalized PSF is attributable to an unresolved nucleus (Fig. 3). Given that the total magnitude of UN J1025-0040 is $K_s = 16.74$, the nucleus has a magnitude of $K_s = 17.1$, and the underlying fuzz has a magnitude of $K_s = 18.0$ (with an uncertainty of at least 0.2 mag). The ISB model suggests that the ratio of starburst to quasar light at K_s-band is ≈ 3. Since 70% of the total K_s-band light is unresolved, a significant part of the starburst must also be unresolved. We see only one nucleus, so a portion of the starburst is within ≈ 2 h^{-1} kpc (in projection) of

[1]DIMSUM is the Deep Infrared Mosaicing Software package, developed by P. Eisenhardt, M. Dickinson, A. Stanford, and J. Ward, which is available as a contributed package in IRAF.

the quasar. The ISB model predicts K_s=17.0, consistent with the unresolved component, but there must be some contribution from the quasar. This implies that part of the starburst may be extended.

5. DISCUSSION

Table 1 summarizes some observed and derived properties of UN J1025−0040. The most straightforward interpretation of our results is that UN J1025−0040 is an interacting galaxy harboring both a quasar and a massive, ∼400 Myr old nuclear starburst. As the first quasar found in tandem with such an *extremely* luminous young stellar population ($M_B = -24.7$), the object's existence alone is of importance. We classify UN J1025−0040 as a "post-starburst" quasar in analogy with "post-starburst" or "k + a" galaxies (Dressler et al. 1999), which display prominent A star populations, but no [O II] λ3727 emission, suggesting they are without on-going star formation.

We do not know for certain that there is no current star formation in UN J1025−0040. The quasar could ionize O^+ to O^{++} (as [O III] λ5007 is seen), and the presence of young, hot stars could be masked by the quasar continuum. We searched the *IRAS* database using ADDSCAN, and found no emission at 60 μm at a level of 0.15 Jy (3σ). The formalism of Sanders & Mirabel (1996) gives $L_{FIR} < 10^{12.4}\ L_\odot$. The bolometric luminosity of the integrated ISB model is $10^{11.6}\ L_\odot$, consistent with the non-detection even if there is significant dust present. UN J1025-0040 sits above the star-forming track on the radio/far-infrared luminosity diagram (van Breugel 1999), where an AGN is expected to account for the large radio emission ($L_{1.4GHz} = 10^{32.2}$ ergs s^{-1} Hz^{-1}). Using the spectral energy distributions of Elvis et al. (1994) to predict a bolometric luminosity for the quasar residual based on its optical flux, we obtain $10^{11.6\pm0.5}\ L_\odot$, the same as that of the ISB model within the uncertainties.

Without an *IRAS* measurement, the dust content is uncertain. Dust is a common feature of starbursts, and there is circumstantial evidence for its presence. The polarization that rises to the red could result from the passage of light through aligned dust grains associated with the starburst, although other hypotheses are viable. Also the dark streak in the fuzz to the SW, while only marginally detected, may represent a dust lane.

The frequency of objects like UN J1025−0040 is unclear, as less extreme versions require detailed observations to recognize. A post-starburst quasar could have been found in previous surveys and misidentified because of low-quality spectra or limited wavelength coverage. Because of its age (∼400 Myr), the starburst could only have been brighter and bluer in the past. Such extreme starbursts have not been identified in previous ultraviolet excess quasar surveys, suggesting that a younger version of UN J1025−0040 might be hidden as a dust-enshrouded ULIRG. If we rerun the ISB model to an age of 55 Myr (old enough that an instantaneous starburst is likely still a good description of the event), the bolometric luminosity is $10^{12.4} L_\odot$, consistent with the infrared luminosity of an ULIRG.

Questions remain that new observations could answer. High-resolution imaging could determine if the starburst is in a circumnuclear ring, a second nucleus, or in a nearby galaxy in a chance alignment. More spectroscopy could determine if the companion object is an interacting galaxy or an intervening star.

6. CONCLUSIONS

UN J1025−0040 is galaxy playing host to both a quasar and a massive starburst. There is intrinsic polarization >1%, increasing toward long wavelengths, perhaps arising from transmission through dust associated with the starburst. This spectacular object may represent a transitional step in an evolutionary sequence between ULIRGs and optically selected quasars.

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TABLE 1
PHOTOMETRY OF UN J1025−0040

Property	Observed	ISB Model[a]	QSO Residual[b]
B[c]	19.3	21.3	19.5
M_B[d]	−24.6	−23.8	−21.9
R[c]	18.3	18.7	19.5
K_s[e]	16.7	17.0	18.5

[a]Instantaneous starburst (ISB) model as in Fig. 3.

[b]The difference between the observations and the ISB model.

[c]Based on the narrow-slit spectra, corrected for Galactic reddening ($E(B-V) = 0.06$ mag). $B = 19.1$ (dereddened) based on our older photometry.

[d]Using $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0$, rest-frame B.

[e]Total, including the fuzz.

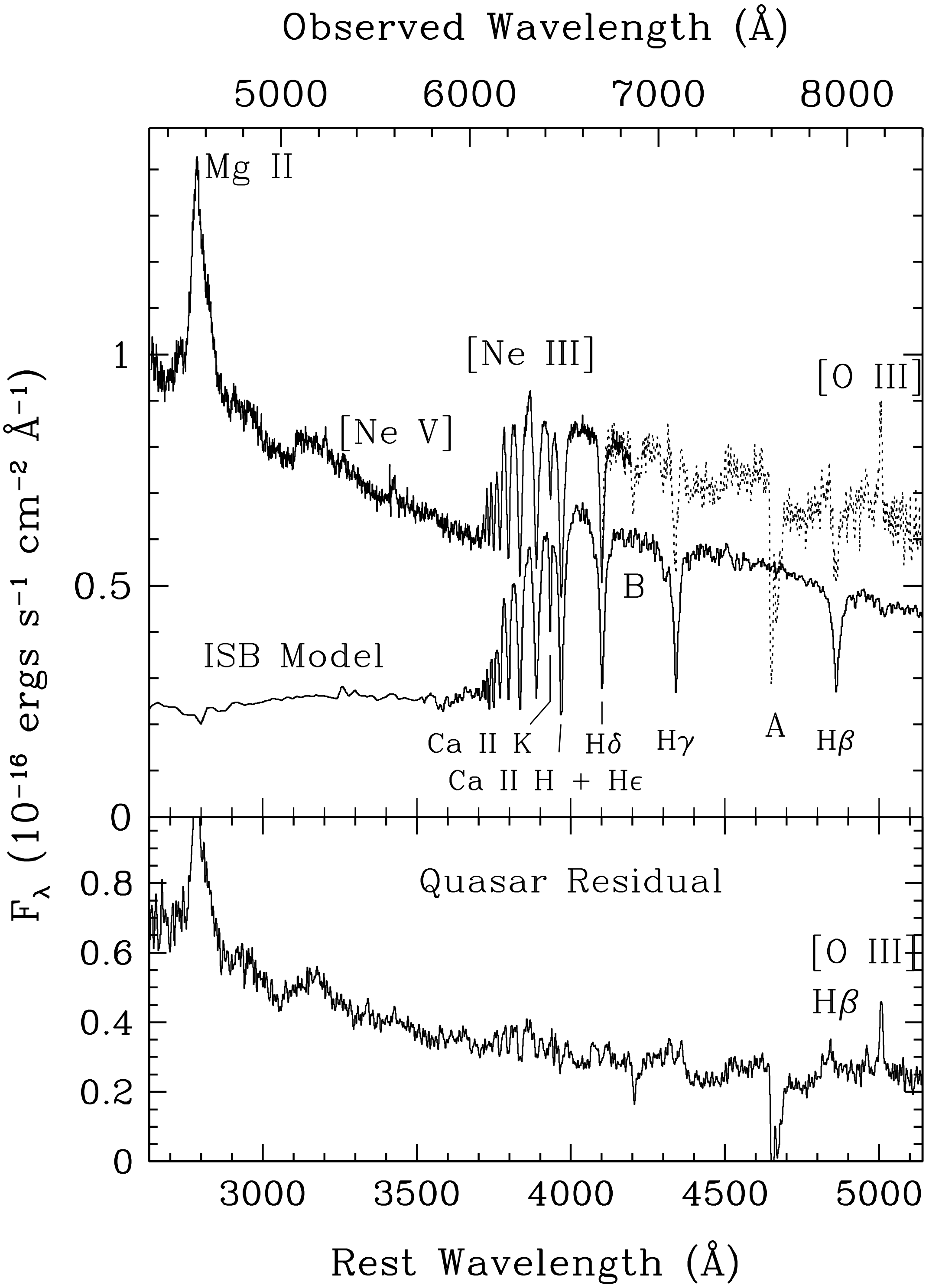

FIG. 1.— Keck spectropolarimetry total-light spectrum (60 minute exposure), with the low-resolution discovery spectrum extending the wavelength coverage (dotted line). Rest-frame wavelengths assume $z = 0.634$. Also plotted is a 400-Myr-old instantaneous starburst (ISB) model described in the text. A and B mark telluric absorption. The bottom panel shows the residual quasar spectrum obtained by subtracting the ISB model from the low-resolution spectrum, revealing broad Hβ emission.

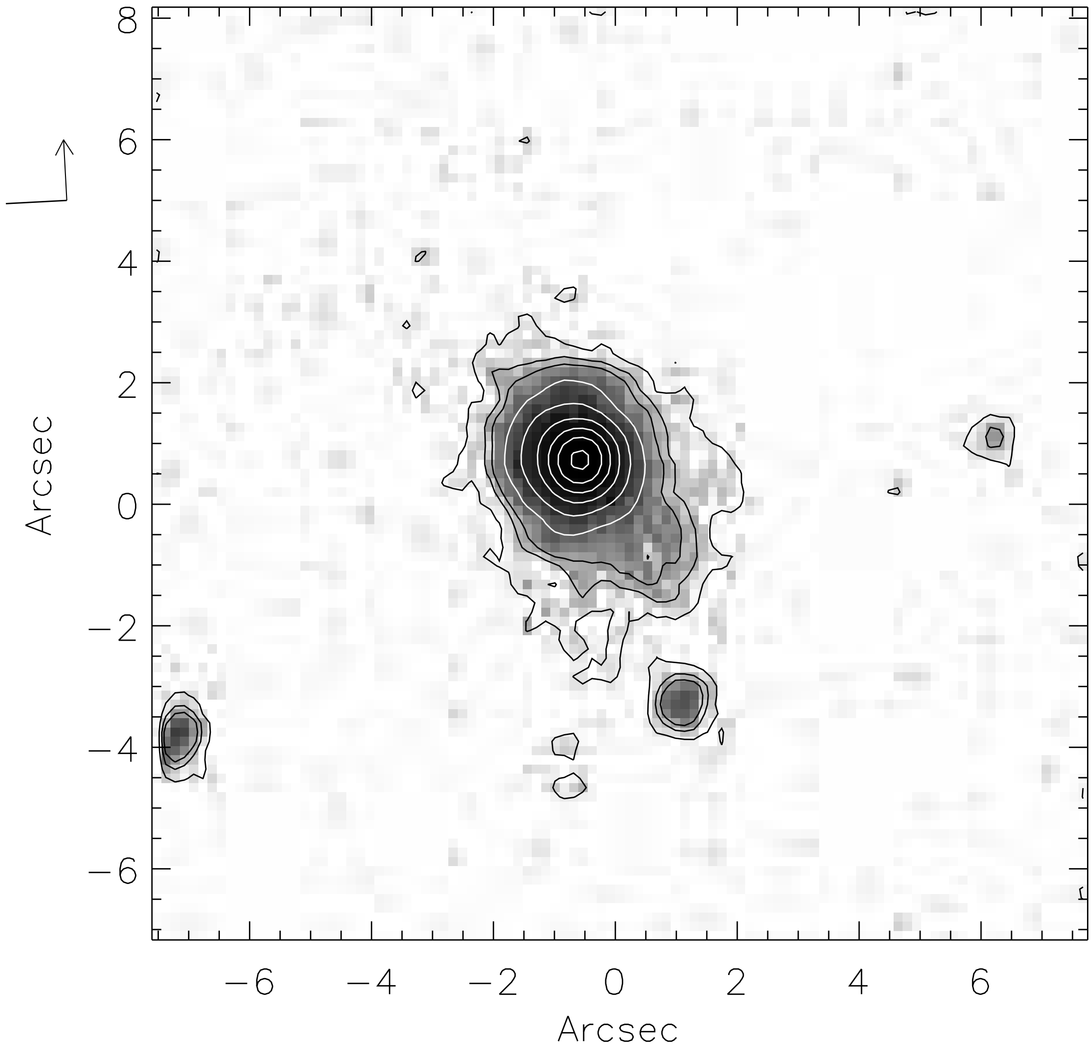

FIG. 2.— Keck K_s-band image (32 min, $\sim 0.5''$ seeing). North (arrow) and East are indicated at left. The outer contour is 22.1 mag/square arcsec. The scale is 4.6 h^{-1} kpc/arcsec ($q_o = 0$).

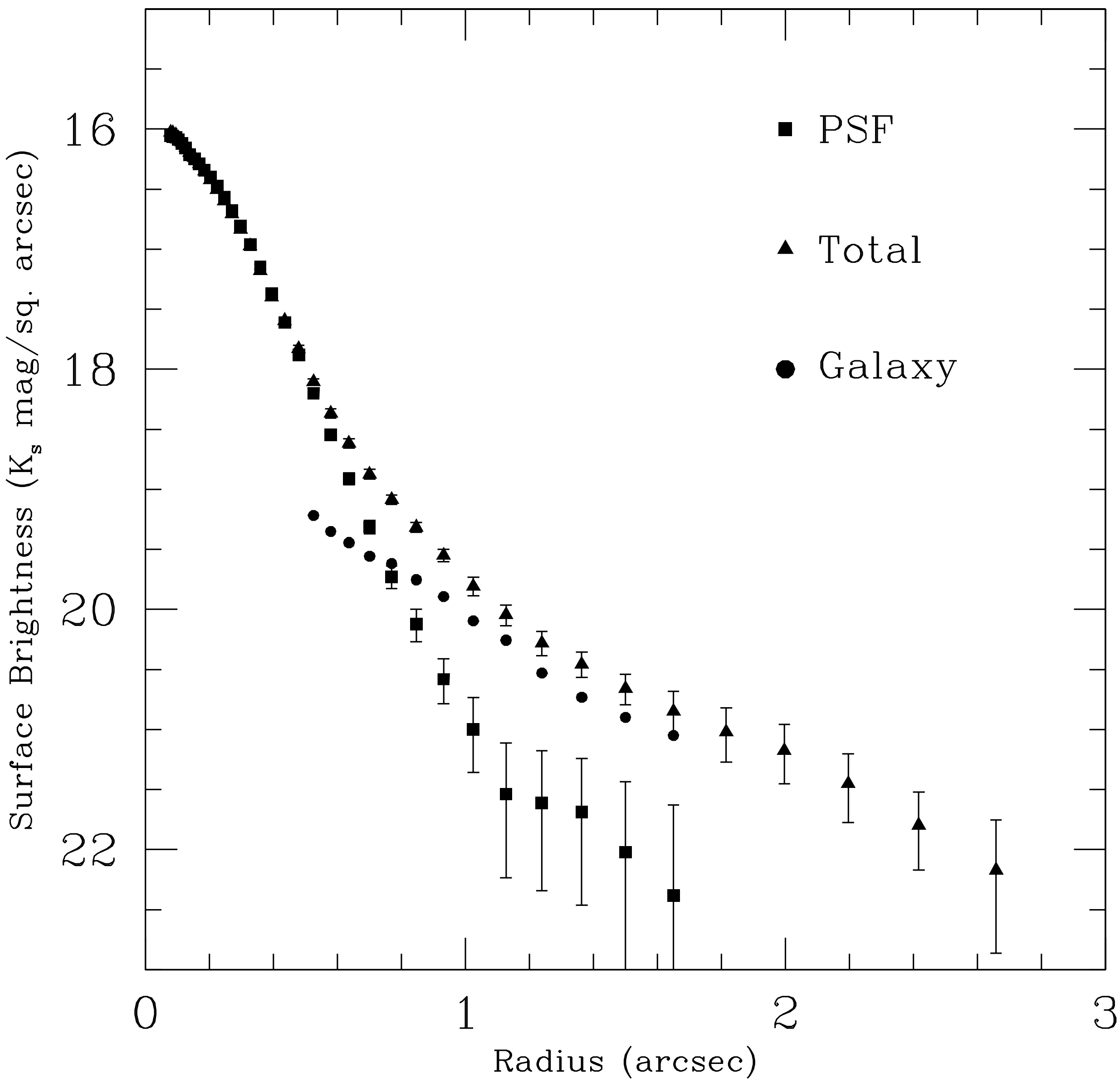

FIG. 3.— Surface brightness profile from ellipse fitting, UN J1025−0040 (triangles) vs. a normalized point source (squares). Filled circles show the difference between the total light and 70% of the normalized PSF.