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# Stellar Distributions Near Sgr A$^*$ and the Host Galaxies of Bright QSOs

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### Abstract

New HST-NICMOS imaging results for the stellar distribution near SgrA$^*$ are presented, indicating a drop in the surface brightness distribution of star light within 1$''$ radius of SgrA$^*$. This could be the result of stellar collisions which deplete giant stars within this radius or indicate the presence of a secondary lower mass black hole. I also describe a new survey for mm-wave CO emission in optically bright PG-QSOs. In 9 out of 12 objects, the interstellar mass of molecular gas is $M_{H2} \geq 1.0 \times 10^9$ $M_\odot$ , with the most massive being $10^{10}$ $M_\odot$ (PG 0050+124 – I Zw 1). This sample was chosen entirely on the basis of low redshift and optical luminosity (and not selected for strong infrared emission), we conclude that *the majority of luminous, low redshift QSOs have gas-rich host galaxies and therefore can not be normal elliptical galaxies*.

## 1.1 $H_2$, H II and Stars within 3 pc of Sgr A$^*$

Within the central few parsecs of our Galaxy, radio, infrared and x-ray observations have revealed a massive black hole lying within a region of ionized 'spiral' arms, encompassed by a ring of dense molecular clouds. The black hole is identified with the non-thermal radio source Sgr A$^*$, and its is estimated to be $2.6\times10^6$ $M_\odot$ from the motions of nearby stars and the neighboring ionized gas (Eckart & Genzel 1996, Genzel et al. 2000, Ghez et al. 2000). At a projected radius of approximately 2 pc from Sgr A$^*$, lies the circumnuclear disk/ring (CND) of dense molecular gas and dust clouds (Genzel et al. 1985, Güsten et al. 1987), and within this ring, ionized gas streams extend down to a few arcsec from Sgr A$^*$ (Lo & Claussen 1983; Lacy et al. 1991). The molecular cloud ring/arms can be modelled as a torus (0.5 pc thick) inclined at 70° to the line of sight (Jackson et al. 1993). Although clearly much less energetic and massive than the luminous AGN seen in many galactic nuclei, this region probably provides our best opportunity to observe in detail the processes associated with buildup of massive black holes and their accretion processes.

We have recently undertaken two investigations aimed at providing the highest resolution imaging of both the ionized and molecular gas in the circumnuclear disk. The molecular gas clouds were imaged in HCN at 3$''$ resolution by Christopher et al. (2002) using the Owens Valley mm-Array; here we present HST-NICMOS imaging at 0.2$''$ resolution of the 1.87$\mu$m P$\alpha$ (HI) emission line. The reduction of the NICMOS images and the subtration of the stellar continuum are described in detail in Scoville et al. (2003a). The extinction in front of the P$\alpha$ emission was estimated from the ratio of the observed P$\alpha$ emission to the $\lambda$

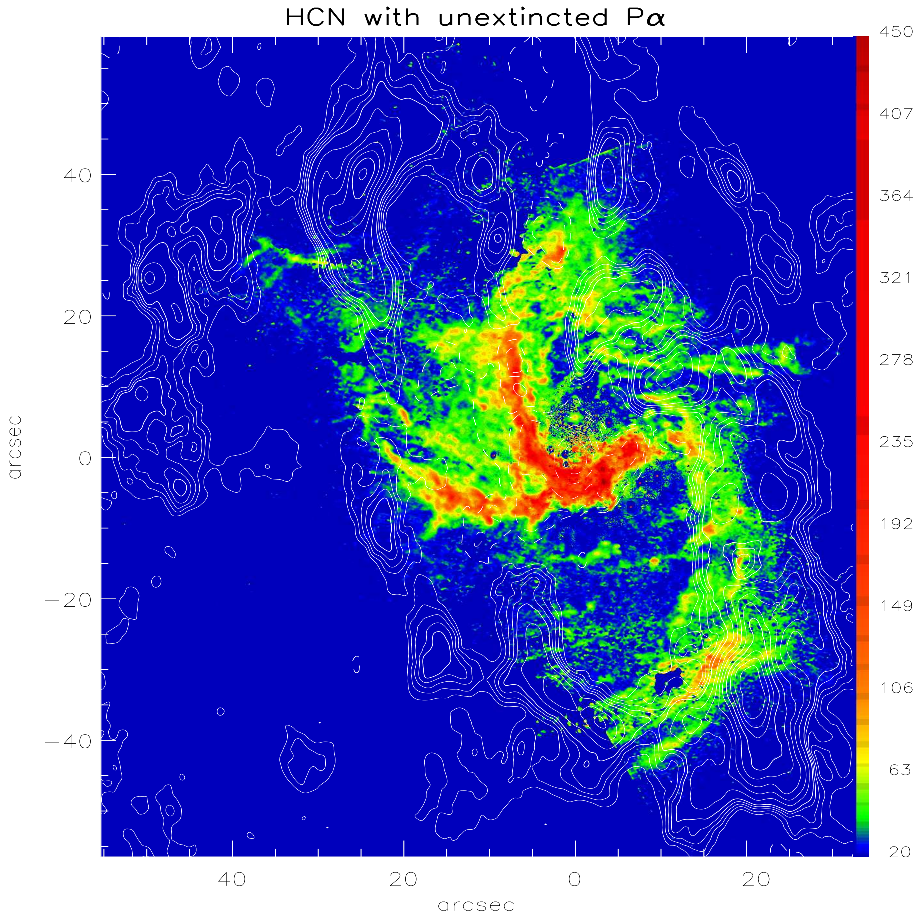


Fig. 1.1. The P$\alpha$ emission corrected for extinction using the extinction derived from the ratio of P$\alpha$ to radio continuum emission . The color scale units are $10^{-16}$ ergs cm$^{-2}$ sec$^{-1}$ per 0.0753$''$ pixel and spatial offsets are relative to Sgr A$^*$. The contours are for the HCN emission at 3$''$ resolution (Christopher et al. 2004).

= 6 cm radio map of Yusef-Zadeh & Wardle (1993). The extinctions range from $A_V \sim 20$ to 50 mag and the median pixel extinction is $A_V$ = 31.1 mag.

Fig. 1.1 shows the extinction-corrected P$\alpha$ emission within 40$''$ of Sgr A$^*$together with contours of 3mm HCN emission mapped with the OVRO array at 3$''$ resolution (Christopher et al. 2004). The prominent ionized emission features in Fig. 1.1 correspond to : the east-west 'bar' structure approximately 7$''$ south of Sgr A$^*$, the northern arm which extends from -2$''$ to over 25$''$ north of Sgr A$^*$, and the western arm approximately 14$''$ west of Sgr A$^*$. With the high resolution and sensitivity of the P$\alpha$ images these large-scale features break up into numerous filaments/arcs which are presumably density enhancements in the ionized gas or individual ionization fronts at the edges of neutral clouds. Smaller scale emission peaks are seen on the 38 emission line stars. The 'mini-cavity' appears as a clearly evacuated spherical hole in the emission of diameter 2.7″ at -1.7″ , -2.8″ from Sgr A* (Yusef-Zadeh, Morris & Ekers 1990).

The mean surface brightness of the star near Sgr A* is shown in Fig. 1.2. Here to avoid the strong effects of bright individual stars, the surface brightness (both mean and median pixel brightness) were computed from the pixels in the lower 80% of the brightness distribution at each radius. (The median also attenuates the effects of a few very bright pixels.) Both the observed and extinction-corrected brightness distributions increase at smaller radii but exhibit a sharp drop at 0.8″ radius, corresponding to 0.03 pc or $1.0\times10^{17}$ cm. To evaluate whether this drop is statistically significant, we independently evaluated the mean and medians for the 4 quadrants (NE, SE, SW, NW) from Sgr A* and then estimated the uncertainties from the standard deviation of these independent samples – these are the vertical error bars shown in Fig. 1.2. The central drop is significant given these uncertainty estimates.

The number density of discrete stars (as opposed to the total light distribution) has been derived as a function of projected radius by Genzel et al. (1996). They also found a decrease in the projected surface density of star counts. For stars with $K \leq 12$ mag, the drop occurs 3″ radius; for brighter star with $K \leq 10.5$ mag, the decrease occurs inside 5″ radius. Thus our results differ significantly from theirs, showing the drop occuring at $\sim$ 0.8″ . Genzel et al. (1996) attribute the decrease at small radii as being due to collisions of the giant stars with main sequence stars which then deplete the giant stars because of their relatively large cross-sections.

To test whether the drop in the surface brightness distribution inside 1″ is due to a lack of a small number of bright giant stars inside 0.8″ , we also show in Fig. 1.2, the median pixel surface brightness. This median flux should be virtually unaffected by the bright stars which dominate a relatively small fraction of the pixels; it still exhibits a modest decrease at small radii, although not as large as that seen in the mean surface brightness.

The drop or leveling off of surface brightness inside 1″ could have several explanations: it might be the core radius of the nuclear stellar distribution or it might be due to the depletion of late type stars with high mass-to-light ratios (Phinney 1989; Bailey & Davies 1999). Gravitational lensing would produce a drop inside the Einstein radius which is on the scale 0.01″ (Wardle & Yusef-Zadeh 1992) and is therefore not a likely explanation. Sellgren et al. (1990) found a diminishing depth of the 2.3$\mu$m CO stellar absorption feature in the central few arcsecs, possibly indication a depletion of giant stars at the center. An alternative possibility is ejection of stars from the central 1″ by a past or present binary black hole (Milosavljević & Phinney – private communication).

## 1.2 The Host Galaxies of QSOs

Despite numerous optical and near infrared studies, the nature of the host galaxies of luminous QSOs has remained a matter of considerable debate since quasars were first discovered in 1964. The host galaxy type provides important clues to the origin and fueling of the supermassive black holes , presumed to be the source of activity and luminosity in QSOs.

Powerful radio galaxies and radio loud quasars appear to be associated with massive elliptical galaxy hosts ($L > L_*$; see Dunlop 2001, Percival et al. 2001). Both their light distributions and dominant old stellar populations are similar to massive E galaxies, consistent with the well-established empirical correlation that nuclear black holes have approximately 0.2 – 0.5 % of the bulge mass (Magorrian et al. 1998, Merritt & Ferrarese 2001), corre-

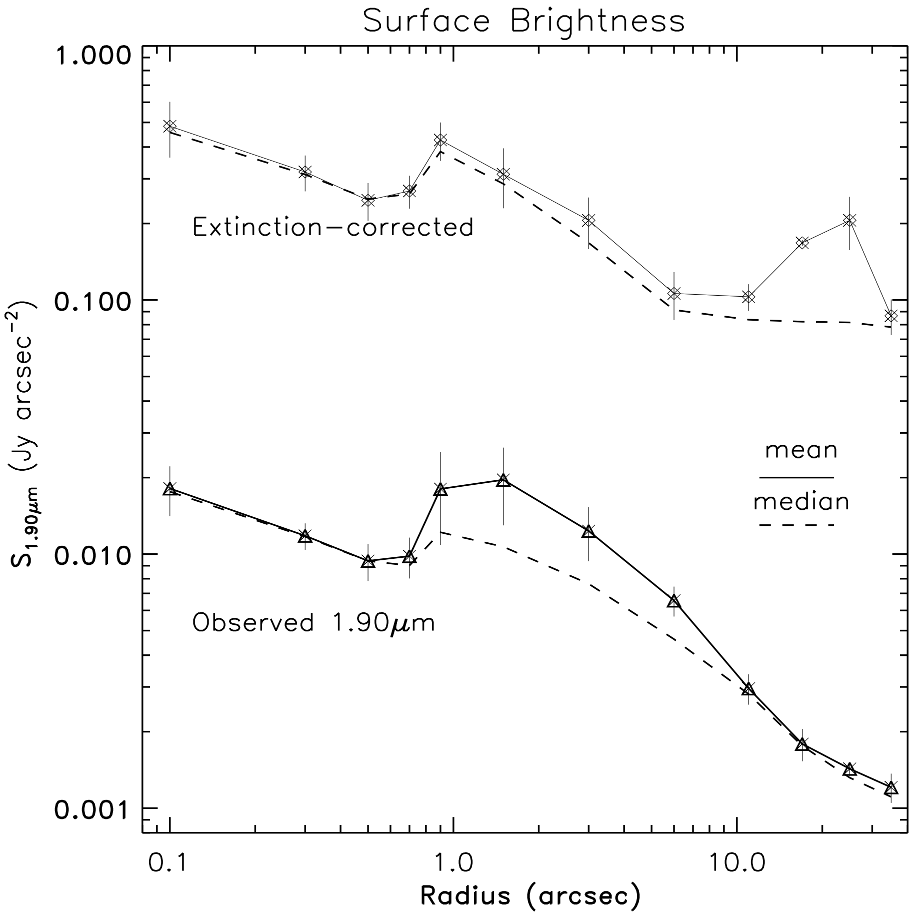


Fig. 1.2. The surface brightness distribution for the observed and extinction-corrected 1.9 $\mu$m radiation is shown. Discrete, bright sources (such as IRS 7) were excluded by removing the brightest 20% of the pixels in each radial bin. Because the noise is very non-Gaussian (dominated by the stellar brightness distribution), the vertical error bars were estimated from the standard deviation of values calculated in the 4 quadrants relative to Sgr A$^*$.

sponding to the nuclear black holes having approximately 0.2-0.5% of the bulge mass. Thus the black hole growth and feeding would appear linked to the stellar bulge and thus a stellar population dominant in elliptical galaxies.

On the other hand, evidence has also accumulated for an evolutionary link between merging ultra-luminous IR galaxies (ULIRGs) and UV/optical QSOs ( Sanders et al. 1988). The evidence includes : similar local space densities for ULIRGs and QSOs; FIR SEDs smoothly transitioning between the two classes (Sanders et al. 1989 & Neugebauer et al. 1986); AGN-like emission lines and significant point-like nuclei (less than 0.2$''$ – Scoville et al. 2000) in 30-40% of the ULIRGs ; and the association of both ULIRGs and some QSOs with galactic interactions (MacKenty & Stockton 1984, Bahcall et al. 1997). In addition, at least one radio-loud QSO, 3C48, shows strong Balmer absorption lines in its extended nebulosity in-

Table 1.1. **PG–QSOs ( z $< 0.1$ , M$_B$ $< -23$ )**

| Name | log[L(FIR)] ($L_\odot$) | z | $D_L$ (Mpc) | $M_{H2}$ ($10^9$ $M_\odot$) |
|---|---|---|---|---|
| **PG1351+640** | 11.82 | 0.088 | 359 | 4.7 |
| **PG1440+356** | 11.62 | 0.078 | 318 | 8.3 |
| **PG0050+124(I Zw 1)** | 11.30 | 0.061 | 248 | 10.2 |
| **PG1404+226** | 11.05 | 0.098 | 401 | 3.2 |
| **PG1426+015** | 10.78 | 0.086 | 351 | 4.5 |
| PG1211+143 | 10.73 | 0.086 | 351 | $< 1.6$ |
| **PG2130+099** | 10.65 | 0.061 | 248 | 2.0 |
| **PG2214+139** | 10.58 | 0.067 | 272 | 1.3 |
| PG1411+442 | 10.52 | 0.089 | 363 | $< 1.7$ |
| **PG0804+761** | 10.35 | 0.100 | 409 | 3.3 |
| PG0844+349 | 10.21 | 0.064 | 259 | $< 0.8$ |
| **PG1229+204** | 10.21 | 0.064 | 259 | 1.1 |

dicating a luminous young stellar population (Boroson & Oke 1984) and mm-CO emission (Scoville et al. 1993).

Perhaps the clearest discrimant between early and late type host galaxies is the host galaxy ISM, particularly the dense ISM probed by mm-CO emission. It is well established that normal E galaxies have molecular gas masses $M_{H2} \leq 10^8$ $M_\odot$ while virtually all late type galaxies have $M_{H2} \geq 5 \times 10^8$ and most have $\geq 10^9$ $M_\odot$ (Young & Scoville 1991; Young & Knezek 1989; Casoli et al. 1998; Georgakais et al. 2001). In contrast to optical/IR imaging, the detection of CO from the host galaxy is not hampered by suppression of the bright quasar nucleus. We report here the results of an extensive survey to detect CO(1-0) emission associated with optically luminous QSOs in order to assess their host galaxy environment (Scoville et al. 2003). Our sample QSOs are from the Palomar-Green (PG) QSO survey including all PG QSOs at z $\leq 0.1$, $M_B \leq -23$ mag and $\delta > 0°$ (Schmidt & Green 1983). This redshift-limited QSO sample contains 12 objects. **The sample was entirely selected based on optical brightness and is not biased toward IR-excess QSOs.**

Out of the nine new PG QSOs observed for CO emission, six were detected at $\geq 3$ $\sigma$ levels. These detections along with upper limits for the remaining sources, are listed in Table 1.

In Table 1, we list the $H_2$ mass estimates for all of the sources in our sample including the three detected previously. The detected QSOs have masses in the range 1.6—10.0 $\times$ $10^9$ $M_\odot$ and the four non-detections have upper limits $\leq 1.5 \times 10^9$ $M_\odot$ . Nine of the 12 sources have now been detected in CO and therefore have gas-rich ISMs, similar to those of late type galaxies or gas-rich merger remnants. In Fig. 1.3, the far infrared luminosities and luminosity-to-mass ratios are shown as a function of derived $H_2$ masses for the 9 Palomar-Green QSOs detected in CO. For a normal spiral galaxy like the Milky Way, the luminosity-to-mass ratio is $\sim 4L_\odot$ / $M_\odot$ and for the most active ULIRG galaxies the ratio is $\sim 200L_\odot$ /

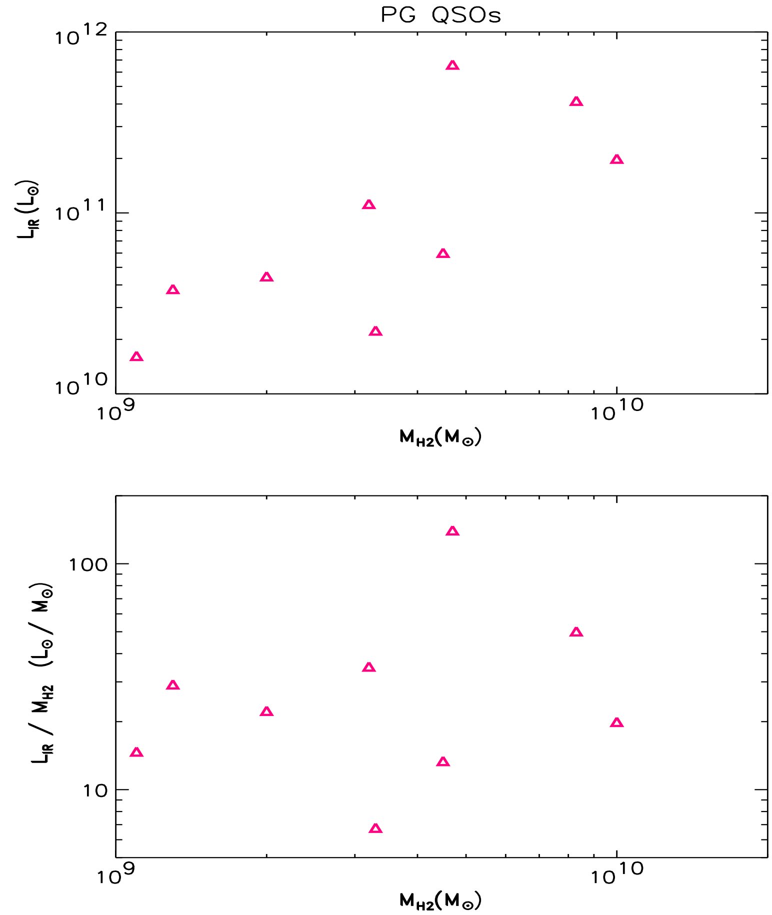


Fig. 1.3. The far infrared luminosities and luminosity-to-mass ratios are shown as a function of derived $H_2$ masses for the 9 Palomar-Green QSOs detected in CO. For a normal spiral galaxy like the Milky Way, the luminosity-to-mass ratio is $\sim 4 L_\odot / M_\odot$ and for the most active ULIRG galaxies the ratio is $\sim 200 L_\odot / M_\odot$ .

$M_\odot$ ; the observed ratios for the PG QSOs are therefore entirely consistent with those of gas-rich normal and starburst galaxies.

It is important to stress that these PG QSOs in our sample were **not IR-selected and therefore, are truly representative of normal optically luminous QSOs with $M_B \leq -23$ mag.** Two thirds of the sample have molecular gas masses more than a factor 10 greater than any local **normal** elliptical or S0 galaxy. The peculiar elliptical/radio galaxy Cen A does have a $H_2$ mass $\sim 10^9 M_\odot$ but it is clear that this is the result of a recent merging with a gas-rich disk galaxy (Mirabel et al. 1999). The clear implication is that these optically luminous QSOs are preferentially in gas-rich disk galaxies or gas-rich merger systems.

Haas et al. (2000) have reached a similar conclusion based on ISO measurements of the far infrared continuum from a sample of 17 PG QSOs. Although similar in motivation, their results are not as easily interpreted in terms of host galaxy type – 10 of the 17 objects were detected with dust masses $\geq 10^7\ M_\odot$ , corresponding to gas masses $\geq 10^9\ M_\odot$ but the sample was generated 'randomly' with a very large range of QSO properties and redshifts. None of their objects overlap with our sample. Barvainis & Ivison (2002) recently completed a submillimeter survey of 40 gravitationally lensed QSOs at Z = 1 – 4.4 and detected 23 at 850 $\mu$m with $M_{dust} \sim 10^{7-8.4}\ M_\odot$ , implying gas masses of $10^{9-10}\ M_\odot$ for standard gas-to-dust ratios. Their important results show no differentiation between radio-loud and quiet AGN and clearly indicate that a significant fraction of high redshift AGNs have very dusty host galaxies. The results obtained here demonstrate that these characteristics persist in the *majority* of optically luminous AGNs at the present epoch with perhaps a factor of 2-3 lower ISM mass.

How might one reconcile this conclusion with the studies using HST imaging which show light profiles in the hosts of the most luminous radio-loud and radio-quiet quasars similar to those of giant elliptical galaxies (Dunlop 2001)? The Dunlop et al. sample had $M_B \leq -23.5$ mag; however, it would hardly seem reasonable that for QSOs only 0.5 mag more luminous, the host galaxy properties should change so fundamentally from mostly disk/merger to old elliptical systems. We note that 3 of the galaxies in our sample also have $M_B \leq -23.5$ mag. The Dunlop et al. result is also inconsistent with that of McLeod & Rieke (1994) who obtained H-band light profiles for the host galaxies in 22 out of 24 local QSOs with $-24.1 \leq M_B \leq -23$. THey found that the majority were fit better by disk profiles than $r^{1/4}$ laws. All of PG QSOs in our study were observed by McLeod & Rieke.

We also note that the $r^{1/4}$ law profile often used to identify elliptical galaxies is a very imprecise indicator of galaxy type, especially for merging systems which are certainly prevalent in the ULIRG samples (Sanders & Mirabel 1996). Scoville et al. (2000) found $r^{1/4}$ law profiles in over 40% of the 24 luminous IR galaxies observed with NICMOS and a similar result was also obtained by Genzel et al. (2001). It is reasonable in the IR luminous galaxies to conclude that the bulge-like light profile was established by dynamical relaxation during the galaxy merging – indeed this is also likely to be the cause of the same light profile in the massive ellipticals which have very likely undergone many merging events. The ULIRG light profiles have typical scale lengths a factor of a few smaller than the largest E galaxies – very likely reflecting the larger mass and larger number of merger events for the most massive E galaxies.

Two possible scenarios linking the ULIRG and AGN phenomena are : 1) that the abundant ISM which fuels the starburst also feeds the central black hole accretion disk or 2) the post starburst stellar population evolves rapidly with a high rate of mass-return to the ISM in the galactic nucleus, leading to sustained fueling of the black hole (e.g. Norman & Scoville 1988). Whether the entire QSO population had precursor ULIRGs (implying that galactic merging is the predominant formation mechanism for AGNs) or only a small fraction of the QSOs are formed by *merging* of ISM-rich galaxies, remains an open question. However, the molecular gas detections reported here make it clear that the highest luminosity and presumably most massive AGNs are generally not in *normal* (ie. gas-poor) ellipticals. Quite plausibly, the same process (galactic merging) which can lead eventually to a relaxed, bulge stellar population also deposits large masses of ISM in the galactic nuclei to feed and buildup massive AGN. The connection between bulge light and central black hole mass (Magorrian et al. 1998, Merritt & Ferrarese 2001) might then be circumstantial rather than a true causal connection between the bulge stellar population and the buildup of the central massive black holes.

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