[O ii] EMISSION IN QUASAR HOST GALAXIES: EVIDENCE FOR A SUPPRESSED STAR FORMATION EFFICIENCY

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ABSTRACT

The [O ii] \lambda3727 line, a commonly used estimator of star formation rate in extragalactic surveys, should be an equally effective tracer of star formation in the host galaxies of quasars, whose narrow-line regions are expected to produce weak low-ionization emission. Quasar spectra generally show little or no [O ii] emission beyond that expected from the active nucleus itself. The inferred star formation rates in optically selected quasars are typically below a few \(M_\odot\) yr\(^{-1}\), and some are significantly less. Quasars do not appear to occur coevally with starbursts. Recent observations, on the other hand, reveal abundant molecular gas in low-redshift quasars. These two results suggest that the star formation efficiency in quasar host galaxies is somehow suppressed during the active phase of the nucleus. The low star formation rates also imply that the nonstellar nucleus powers the bulk of the thermal infrared emission in radio-quiet quasars.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — quasars: general

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1 INTRODUCTION

The discovery of scaling relations between central black hole masses and the bulge properties of their host galaxies (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000) has stimulated a plethora of ideas linking black hole growth with galaxy assembly (see reviews in Ho 2004). If the evolution of black holes and galaxies are as closely coupled as currently thought, one would expect black hole accretion to show some empirical connection with star formation. Two recent lines of evidence point in this direction. From an analysis of a large sample of emission-line galaxies selected from the Sloan Digital Sky Survey, Kauffmann et al. (2003) find that narrow-line (type 2) active galactic nuclei (AGNs) frequently show stellar absorption-line features indicative of young-to-intermediate-age stars, with the frequency of young stellar populations growing stronger with increasing AGN luminosity. In a parallel development, studies of quasar spectra continue to support the notion that their emission-line regions are preferentially associated with the stellar population in the central regions of the host galaxies (Hamann et al. 2004 and references therein).

It is obviously of considerable interest to directly measure the star formation rate (SFR) concurrent with quasar activity. The existing studies on the stellar content of quasar host galaxies have been primarily restricted to stellar populations belonging to the poststarburst phase (e.g., Canalizo & Stockton 2001; Brotherton et al. 2002; Kauffmann et al. 2003), or older (Nolan et al. 2001). The main challenge in studying the youngest stellar population in AGNs is that nearly all the observational tracers commonly used to estimate SFRs in galaxies, such as hydrogen recombination lines or continuum emission in the ultraviolet, radio, or far-infrared (IR) bands, suffer from severe contamination by emission from the AGN itself, if the latter is sufficiently strong, as it is in quasars. As described in this paper, however, there is one important exception.

[O ii] \lambda3727, a prominent nebular emission line in H ii regions, is widely used to track star formation in galaxy surveys, particularly for redshifts \(z \gtrsim 0.4\) (e.g., Lilly et al. 1996; Hippelein et al. 2003). Its use as a SFR indicator has been discussed by Gallagher et al. (1989) and Kennicutt (1998), and it has recently been examined extensively by, among others, Kewley et al. (2004). Can [O ii] be used to measure SFRs in AGNs?

Now, [O ii] emission is by no means uniquely produced in H ii regions. The narrow-line regions of AGNs emit [O ii], which can be especially prominent in photoionized nebulae characterized by low-ionization parameters or in a shock-heated plasma (Ferland & Netzer 1983; Halpern & Steiner 1983; Ho et al. 1993a). On the other hand, in narrow-line regions governed by high-ionization parameters, such as those pertinent to Seyfert galaxies, [O ii] is observed and predicted to be relatively weak. For a plausible range of ionization parameters, densities, and ionizing spectra, the intensity of [O ii] \lambda3727 is a small, roughly constant fraction of [O iii] \lambda5007 (~10%–30%), as observed (Ferland & Osterbrock 1986; Ho et al. 1993a, 1993b). The physical conditions of the narrow-line regions of quasars have been less thoroughly studied, but they are thought to be similar to those of Seyfert galaxies (Wills et al. 1993). The approximate constancy of the [O ii]/[O iii] ratio in high-ionization AGNs (whose ionization parameter can be independently gauged by, e.g., the [O iii]/H\beta ratio) thus suggests a simple strategy for estimating SFRs in luminous AGNs such as Seyfert 1 nuclei and quasars: any [O ii] emission in excess of the component intrinsic to the AGN, as constrained by the [O iii] strength, can be reasonably attributed to star formation.

This paper draws attention to the fact that optically selected quasars exhibit weak [O ii] emission. The absence of [O ii] emission in excess of the baseline level expected from nonstellar photoionization indicates that strong star formation generally does not accompany quasar activity. Since nearby quasars harbor significant amounts of molecular gas, their low SFRs suggest that nuclear activity somehow curtails the star formation efficiency in these systems. The independent estimate of SFR based on [O ii] also helps to clarify the energy source responsible for the IR emission in quasars.

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1 The ionization parameter is defined as the ratio of the density of Lyman continuum photons to the density of hydrogen.
2. OBSERVATIONAL CONSTRAINTS

The [O II] λ3727 line has not been extensively studied in quasars. Unlike [O II] λ5007, which is often prominent in quasars, [O II] tends to be quite weak, in many cases eluding detection. Radio-loud quasars can have [O II] luminosities as high as \( L_{[\text{O II}]} \approx 10^{42} - 10^{43} \) ergs s\(^{-1}\) (Wills et al. 1993; Hess et al. 1996). By contrast, nearby radio-quiet quasars from the Palomar-Green (PG) survey (Schmidt & Green 1983) typically have \( L_{[\text{O II}]} \approx 10^{40} - 10^{42} \) ergs s\(^{-1}\), with many objects having upper limits near \( L_{[\text{O II}]} \approx 10^{41} \) ergs s\(^{-1}\) (Simpson et al. 1996; Wilkes et al. 1999; Kuraszkiewicz et al. 2000). In cases where both [O II] and [O III] are observed, [O II]/[O III] \approx 0.1 - 0.3, which is within the range expected solely from AGN photoionization. We can arrive at a statistically more robust result by examining ensemble averages of large quasar samples, as depicted in composite spectra generated from extensive surveys such as the Large Bright Quasar Survey (LBQS; Francis et al. 1991), the FIRST Bright Quasar Survey (Brotherton et al. 2001), the Sloan Digital Sky Survey (Vanden Berk et al. 2001; Richards et al. 2003; York et al. 2004), and the Two Degree Field (2dF) and Six Degree Field (6dF) Quasar Redshift Surveys (Croom et al. 2002). A consistent pattern emerges: [O II] is invariably quite weak (rest-frame EW \( \approx 2 \) Å), ~10% - 20% in strength compared to [O II]. To estimate the absolute strength of [O II], consider the LBQS composite, which comprises mostly quasars with \( (M_B) \approx 23.5 \) mag at \( z \approx 1.3 \). For \( EW([\text{O II}]) = 1.9 \) Å and a continuum spectrum \( f_C \propto \lambda^{-0.32} \) (Francis et al. 1991), we find \( (L_{[\text{O II}]} = 9.8 \times 10^{41} \) ergs s\(^{-1}\)).

3. IMPLICATIONS

3.1. Star Formation Rate and Efficiency

The observations summarized in §2 show that [O II] emission in quasars is generically quite weak. When present, its strength relative to [O III] is entirely consistent with a pure AGN origin, leaving little room for any additional contribution from ongoing star formation in the host galaxy. We can use the existing [O II] measurements to place limits on the SFRs, employing the calibration of Kewley et al. (2004, eq. [10]), which explicitly takes into account extinction and metallicities:

\[
\text{SFR}([\text{O II}]) = \frac{7.9 \times 10^{-42} (L_{[\text{O II}]/\text{ergs s}^{-1}})}{16.73 - 1.75 \log([\text{O III}]/[\text{H} II]) + 12} \times \log(M_\odot) \text{ yr}^{-1}.
\]

Here \( L_{[\text{O II}]} \) is the extinction-corrected [O II] luminosity, and the solar oxygen abundance is assumed to be \( log([\text{O III}]/[\text{H} II]) = 12 = 8.9 \). We make three assumptions: (1) [O II] is attenuated on average by \( A_V = 1 \) mag, a value commonly deduced in surveys of star-forming galaxies (e.g., Sullivan et al. 2000); (2) the line-emitting gas has a characteristic metallicity of twice solar, which lies near the upper end of the values inferred for AGN narrow-line regions (Storchi-Bergmann et al. 1998); and (3) one-third of the [O II] emission comes from H II regions, which is a conservative upper bound, since in reality the observed [O II]/[O III] ratios (0.1 - 0.3) strongly indicate that most or all of the [O II] can be accounted for by the AGN. Then, an observed [O II] luminosity of \( 10^{41} \) ergs s\(^{-1}\), a value around which most of the current detections and upper limits for PG quasars cluster, translates into a SFR of \( 1 M_\odot \text{ yr}^{-1} \). For the LBQS composite spectrum (§2), we obtain SFR \( \approx 10 M_\odot \text{ yr}^{-1} \).

These are interesting limits, considering that nearby, normal spiral galaxies (Solomon & Sage 1988), including the Milky Way (Scoville & Good 1989), have SFRs \( \approx 1 - 3 M_\odot \text{ yr}^{-1} \).

The low SFRs deduced for the quasar host galaxies seem, at first glance, quite surprising. With their nuclei fully shining as powerful AGNs, one would naively expect the host galaxies to be quite plentiful in gas and hence forming stars at a rate substantially higher than in quiescent disk galaxies. A possible resolution perhaps can be found by appealing to an evolutionary scenario, such as that proposed by Sanders et al. (1988), whereby quasars emerge as the endpoint of major, gas-rich mergers. Most of the gas is consumed first in a vigorous starburst phase, when the system appears as an ultraluminous IR galaxy. By the time the quasar emerges, the starburst has subsided, most of the gas has been exhausted, and any residual gas might be expelled by the AGN.

While such a picture has theoretical support from numerical simulations of galaxy mergers that include AGN feedback (Springel et al. 2005), it appears to be in serious conflict with the observed gas content of nearby quasars. Scoville et al. (2003), in an unbiased survey of optically selected (PG) quasars with \( z < 0.1 \), detected abundant CO (1 - 0) emission in the majority (9/12) of the sources. With a standard Galactic CO-to-H2 conversion factor, the derived molecular gas masses range from \( \approx 10^9 \) to \( 10^{10} M_\odot \). Far from being depleted of cold interstellar medium, nearby quasars are, in fact, quite gas-rich. For comparison, nearby disk galaxies contain \( M_{\text{H}_2} \approx (2 - 4) \times 10^9 M_\odot \) (Solomon & Sage 1988). Indeed, we are now faced with a new puzzle. Why do quasar host galaxies form so few stars in spite of having significant amounts of molecular gas? To quantify this apparent contradiction, we have examined 25 low-z PG quasars with available [O II] and CO data (Table 1). Consistent with the above discussion, the majority of the objects have SFRs or limits thereof that are quite modest, ranging from less than \( 1 M_\odot \text{ yr}^{-1} \) to a few \( M_\odot \text{ yr}^{-1} \).

Gas-rich galaxies ordinarily obey a well-defined correlation between their far-IR luminosity and CO luminosity, or, equivalently, between their SFR and molecular gas mass. The ratio of these two quantities yields an estimate of the star formation “efficiency” (e.g., Young et al. 1986). This is illustrated in Figure 1, where the solid line demarcates the locus occupied by isolated or weakly interacting galaxies (Solomon & Sage 1988). For comparison, we have superposed a sample of luminous (Sanders et al. 1991) and ultraluminous (Solomon et al. 1997) IR galaxies to illustrate the familiar result that these objects, most of which are mergers or strongly interacting systems, have elevated star formation efficiencies. In this context, it is remarkable that nearly all (23/25) of the PG quasars lie at or below the locus of normal galaxies. Recall that the SFRs for the PG quasars already should be viewed as conservative upper limits, since the [O II]/[O III] ratios (Table 1) suggest that star formation contributes negligibly to the [O II] emission. Taken at face value, the host galaxies of nearby quasars appear to form stars far less efficiently than would be expected on the basis of their gas content. Their star

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2. Adopt the following cosmological parameters: \( H_0 = 72 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \).

3. Throughout this paper, SFRs refer to a Salpeter stellar initial mass function with a lower mass limit of 0.1 \( M_\odot \), and an upper mass limit of 100 \( M_\odot \).

4. Since the [O II] measurements were obtained using apertures (\( \approx 2'' - 5'' \)) that are typically smaller than the optical extent of the host galaxies, the quoted [O II] strengths are probably lower limits to the total line luminosity from these objects. The current comparison with the CO data, however, is valid because the CO maps have a resolution of \( \approx 4'' \), and most of the emission remains unresolved on this scale (Evans et al. 2001; Scoville et al. 2003). Three of the objects (PG 1119+120, PG 1229+204, and PG 1404+226) technically fall below the traditional luminosity criterion for quasars \( M_B < -23 - 5 \log(h_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = -22.2 \) mag for our choice of \( h_0 \), but this historical definition is arbitrary and has no particular physical significance.
formation efficiencies certainly fall short of those in strongly interacting galaxies (by a factor \(\sim 20\)–50), but, more strikingly, they are suppressed even relative to normal galaxies (by a factor \(\gtrsim 5\)).

What could be responsible for the anomalously low star formation efficiencies in quasar host galaxies? As reviewed by Maloney (1999), the hard radiation field of an AGN can have a profound impact on the thermal and ionization structure of a molecular cloud. Although the details have not been elucidated, it is not unreasonable to suppose that this form of AGN feedback could have direct consequences for a molecular cloud's ability to form stars.

### 3.2. Origin of Far-Infrared Emission in Quasars

Our results have some bearing on the origin of the IR emission in quasars. While the IR continuum of quasars, at least of the radio-quiet variety, can be explained largely by thermal emission from dust reradiation, the primary energy source for the far-IR emission is still controversial (e.g., Haas et al. 2003). The \([\text{O} \, \text{ii}]\) measurements discussed above provide an independent constraint on this problem. Table 1 lists the IR luminosity predicted from our limits on the SFR, which, as expected, in almost all cases is quite small compared to the total observed IR luminosity. Although the PG quasars in Figure 1 indeed do roughly follow the track of IR-luminous galaxies in terms of their total IR luminosity, it would be misleading to conclude that the IR emission necessarily originates from stellar heating (e.g., Yun et al. 2004). The true contribution to the IR emission due to star formation, as inferred here, it seems difficult to escape the conclusion that accretion energy powers the bulk of the IR continuum.

### 3.3. Comparison with Previous Work

The main result of this paper—that quasar host galaxies experience low levels of ongoing star formation—may appear to be at odds with other works in the literature that have inferred high SFRs in quasars. In a study of composite spectra generated from the 2dF+6dF Quasar Redshift Surveys, Croton et al. (2002) conclude that the majority of the \([\text{O} \, \text{ii}]\) emission in low-luminosity (\(M_g \approx -20\) mag) objects probably comes from star-forming regions in the host galaxy and not from the AGN. These authors speculate that the same may hold in high-luminosity sources. From the observed inverse correlation between \([\text{O} \, \text{ii}]\) EW and...
luminosity, and the somewhat steeper dependence between Ca \textsc{ii} K absorption EW and luminosity, the assumption of a constant host galaxy spectrum suggests that the AGN contributes an increasingly larger fraction of the [O \textsc{ii}] flux in higher luminosity sources. This is consistent with the variation of the relative strengths of [O \textsc{ii}] and [O \textsc{iii}] as a function of luminosity. From Figure 7 of Croom et al., [O \textsc{ii}]/[O \textsc{iii}] has a relatively high value of $\sim 0.4$ in the low-luminosity bin, as expected for significant host galaxy contribution, but decreases to $\sim 0.1$ at $M_B \approx -24$ mag, a value more typical of AGNs. Independent of the exact interpretation, however, we note that the absolute strength of [O \textsc{iii}] in the 2Df+6dF composites nonetheless indicates that the line luminosity, and thus the SFR, is quite modest. The high-luminosity AGN composite spectra from 2Df+6dF have EW([O \textsc{iii}]) $\approx 2$ Å and span $z \approx 1-2$, not unlike the LBQS composite (Francis et al. 1991) discussed in §§ 2 and 3, and hence our previous limit on the SFR for the latter applies.

Netzer et al. (2004) recently obtained [O \textsc{ii}] $\lambda$5007 measurements of luminous, high-redshift quasars in order to investigate the properties of their narrow-line regions. From the subset of their sample that shows strong [O \textsc{iii}] emission, Netzer et al. deduced that the narrow-line region in these objects must be exceptionally dense compared to the conditions in nearby, less luminous AGNs. They postulate that the high-density gas might be related to, or supplied by, star-forming regions. However, this conjecture for the origin of the dense gas, while plausible, is not unique, as Netzer et al. recognize. One can envision many possible channels for delivering dense gas to the circumnuclear environment of galaxies without implicating nuclear starburst activity. Moreover, even if star formation were ultimately linked to the origin of the gas, in the absence of a specific model one cannot rule out a scenario wherein the starburst precedes the quasar phase.

As reviewed by Heckman (2004), there has been mounting evidence from spectroscopic studies of nearby AGNs that nuclear and starburst activities are closely coupled. The most extensive treatment of this problem comes from the analysis of the Sloan Digital Sky Survey database by Kauffmann et al. (2003), who find that the host galaxies of luminous type 2 AGNs often show spectral signatures typical of young-to-intermediate-age stars. Although more difficult to study, broad-line (type 1) objects qualitatively behave the same (Kauffmann et al. 2003). These results are not in conflict with the findings of this study. The stellar population uncovered by Kauffmann et al. has a characteristic age of $10^8 - 10^9$ yr, which is indicative of a post-starburst population, whereas our study specifically aims to address the younger ($\leq 10^7$ yr), ionizing population.

Finally, there has been considerable success in efforts to detect thermal dust emission through submillimeter observations of high-redshift ($z \gtrsim 2$) quasars (Omont et al. 2004 and references therein). It is customary to invoke enormous SFRs, $\sim 10^5 M_\odot$ yr$^{-1}$ or more, to account for the far-IR luminosities ($\gtrsim 10^{13} L_\odot$) observed in these sources, especially when CO emission is detected. While the presence of a sizable molecular gas reservoir is clearly a necessary prerequisite for a starburst, and undoubtedly indicates the galaxy’s future potential to form stars, our study shows that this, by itself, is not a sufficient condition for a starburst—not when a powerful quasar is simultaneously active. As discussed in § 3.2, the interpretation of far-IR emission can be ambiguous. The technique outlined in this paper can be applied directly to evaluate the SFRs in distant quasars, by searching for [O \textsc{ii}] $\lambda$3727 emission shifted into the near-IR.

### 3.4. Caveats

We conclude with a brief discussion of possible sources of systematic error that may affect the results presented in this paper. First, it is possible that we have underestimated the magnitude of dust extinction on the [O \textsc{ii}] measurements. We have assumed that quasar host galaxies on average are affected by roughly the same degree of extinction as commonly deduced in actively star-forming galaxies. There is no compelling reason, however, to believe that this is a poor approximation. The amount of dust obscuration in galaxies correlates with the level of star formation, but for SFRs $\lesssim 100 M_\odot$ yr$^{-1}$, appropriate for all but the most extreme starbursts, optical SFR tracers such as [O \textsc{ii}] and H$_\alpha$ indicate extinction corrections of only a factor of 4–5 (e.g., Dopita et al. 2002; Cardiel et al. 2003; Hopkins et al. 2003), which is consistent with our adopted value of $A_V = 1$ mag. In order to explain the apparent offset of the quasars in Figure 1, we would need to increase the extinction to $A_V = 2$ mag to match the normal galaxies, and to $A_V = 3-4$ mag to be consistent with the IR-bright starbursts. It is worth reiterating that our estimates of SFRs have, if anything, erred on the side of caution by assuming that as much as one-third of the [O \textsc{ii}] emission arises from H \textsc{ii} regions, although the observed [O \textsc{ii}]/[O \textsc{iii}] ratios are manifestly consistent with an AGN origin.

It could be objected that the comparison between quasars and star-forming galaxies in Figure 1 is exaggerated because it invokes two vastly different methods of estimating SFRs, namely [O \textsc{ii}] and far-IR luminosity. While it would certainly be
worthwhile to revisit this analysis once globally integrated [O ii] measurements become available for quiescent and ultraluminous IR galaxies, here we simply note that the magnitude of the trend observed in Figure 1 cannot be explained by possible residual systematic differences between the two methods after reasonable precautions are taken to correct for extinction in [O ii]. The scatter between the SFRs derived from the two methods (~0.25 dex; Kewley et al. 2002, 2004; Hopkins et al. 2003) is small compared to the observed scatter in Figure 1.

As emphasized by Kewley et al. (2004), SFRs based on [O ii] can be influenced by metallicity. Although we have no direct information on the metallicity of the [O ii]-emitting gas for our objects, we have made a reasonable guess (twice solar) based on detailed studies of nearby AGNs (Storchi-Bergmann et al. 1998) and on the expectation that the host galaxies of quasars should be relatively massive and hence metal-rich. Artificially increasing the metallicity to 3–4 times solar would not qualitatively alter our basic conclusions.

It is conceivable that quasar host galaxies do experience significantly higher SFRs, but somehow most of the H ii regions, perhaps as a result of being exposed to the strong radiation field of the AGN, are not being properly traced through [O ii] emission. One might also appeal to unusually high nebular densities to quench the [O ii] emission by collisional de-excitation. Both possibilities are purely speculative and difficult to test, but they merit further investigation.

The H2 masses for the quasars were derived using a standard CO-to-H2 conversion factor appropriate for Galactic molecular clouds. While this is a perennial source of concern, its impact is mitigated by the fact that our conclusion concerning star formation efficiency in quasars is based on a differential comparison with other galaxies whose H2 masses were derived from the same premise. Of course, we cannot exclude the possibility that quasar host galaxies have a systematically different (lower) CO-to-H2 conversion factor than other extragalactic systems. Downes & Solomon (1998) have argued, for example, that the CO-to-H2 conversion factor in ultraluminous IR galaxies may be up to a factor of 5 lower than the Galactic value. There is no reason to suspect, however, that the extreme conditions in ultraluminous IR galaxies should apply to the quasars considered here. Moreover, the gas masses deduced using the standard CO-to-H2 conversion factor, when compared with the dust masses derived from IR observations, lead to reasonable gas-to-dust ratios (Haas et al. 2003; Scoville et al. 2003). In order to align the quasars with the trend defined by the normal galaxies in Figure 1, the H2 masses for the quasars would have to be lowered by roughly an order of magnitude.

4. SUMMARY

This paper discusses the feasibility of using the [O ii] λ3727 emission line as a tracer of ongoing star formation in AGNs, particularly in the high-ionization regime pertinent to Seyfert galaxies and quasars. From an assessment of the existing spectroscopy on quasars, we find that quasars exhibit very weak [O ii] emission, with little or no contribution evident from star-forming regions in the host galaxy. Quasar and starburst activity do not appear to be coeval. For a well-defined sample of nearby, optically selected quasars with detected CO emission, the low inferred star formation rates coupled with the abundant molecular gas suggest that star formation in these objects is inefficient, perhaps as a consequence of AGN irradiation. The low star formation rates also imply that the bulk of the IR emission in radio-quiet quasars must be powered by accretion energy rather than by young stars.

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