COMPLETION OF A SURVEY AND DETAILED STUDY OF DOUBLE-PEAKED EMISSION LINES IN RADIO-LOUD ACTIVE GALACTIC NUCLEI

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ABSTRACT

We report the completion of a survey of radio-loud active galactic nuclei (AGNs) begun in an earlier paper with the main goal of finding and studying broad, double-peaked Balmer lines. We present H\textsc{\textalpha} spectra of 13 more broad-lined objects, including three with double-peaked H\textsc{\textalpha} profiles. The final sample includes 106 radio-loud AGNs. In our final census 20\% of objects have H\textsc{\textalpha} lines with double peaks or twin shoulders (the "double-peaked emitters"), and of these 60\% (the disklike emitters) can be fitted quite well with a model attributing the emission to a circular, relativistic, Keplerian disk. In four objects where broad H\beta and Mg\textsc{\textpi} lines have been observed, we compare the profiles with models of photoionized accretion disks and find them to be in reasonable agreement. We reaffirm the conclusion of Paper I that double-peaked emitters stand out among radio-loud AGNs on the basis of a number of additional properties that they possess: (1) an unusually large contribution of starlight to the optical continuum around H\textsc{\textalpha}, (2) unusually large equivalent widths of low-ionization lines ([O\textsc{i}] and [S\textsc{ii}]), (3) unusually large [O\textsc{i}]/[O\textsc{iii}] ratios, and (4) Balmer lines that are on average twice as broad as those of other radio-loud AGNs and preferentially redshifted. We consider and evaluate models for the origin of the lines, and we find accretion disk emission to be the most successful one because it can explain the double-peaked line profiles and it also offers an interpretation of the additional spectroscopic properties of these objects. We find the alternative suggestions (binary broad-line regions, bipolar outflows, anisotropically illuminated spherical broad-line regions) unsatisfactory because (1) they fail direct observational tests, (2) they cannot explain all of the unusual properties of disklike emitters self-consistently, or (3) in one case the physical foundations appear to be unsound. We suggest that double-peaked emitters and accretion-powered LINERS are the segment of the AGN population in which the accretion rate is considerably lower than the Eddington rate, with the consequence that the inner accretion disk takes the form of an ion torus and the wind that normally enshrouds the disk proper is absent.

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1. INTRODUCTION

In our current working picture of active galactic nuclei (AGNs) the underlying power source is thought to be a supermassive black hole, which is accreting matter from the host galaxy. The accretion flow very close to the central object is believed to form an equatorial accretion disk, by analogy with stellar accretion-powered systems such as cataclysmic variables and low-mass X-ray binaries. The presence of accretion disks in AGNs, although appealing from a theoretical perspective and generally assumed, had received only limited and indirect observational support until a few years ago, when direct dynamical evidence became available. This evidence comprises double-peaked line profiles characteristic of matter rotating in a disk, much like the double-peaked emission lines of cataclysmic variables (see, for example, Young & Schneider 1980; Young, Schneider, & Shectman 1981; Marsh 1988).

A number of authors (e.g., Oke 1987; Pérez et al. 1988; Chen, Halpern, & Filippenko 1989; Chen & Halpern 1989; Halpern 1990) had proposed that the double-peaked Balmer lines found in the optical spectra of a handful of broad-line radio galaxies such as 3C 390.3, Arp 102B, and 3C 332 originate in accretion disks around supermassive black holes at the centers of these galaxies. We thus carried out a spectroscopic survey of almost 100 moderate-redshift broad-line radio galaxies and radio-loud quasars (Eracleous & Halpern 1994, hereafter Paper I) and discovered 19 new double-peaked Balmer lines of which a dozen conformed with a simple, kinematic accretion disk model. We also found that such objects stand out on the basis of additional spectroscopic properties of their hosts. Independent dynamical evidence for a disklike accretion flow in the immediate vicinity of the central black hole (within a hundred gravitational radii) has been provided by X-ray spectroscopy of Seyfert galaxies with \textit{ASCA}. The profiles of the Fe K\textsubscript{\alpha} lines of almost all Seyfert galaxies observed with \textit{ASCA} are extremely broad and asymmetric with full widths at zero intensity approaching a third of the speed of light ( Mushotzky et al. 1995; Tanaka et al. 1995; Nandra et al.

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1997). In most cases the line profiles can be described very well by models attributing the emission to the inner parts of a relativistic accretion disk.

We have continued to observe radio-loud AGNs in search of double-peaked emitters and in order to extend our tests of models for the origin of their broad Balmer lines. In this paper we report the completion of the survey begun in Paper I and the refined conclusions from it. We make use of new spectroscopic data that we have obtained, as well as a great deal of information on double-peaked emitters from recent multiwavelength surveys. We also take into consideration some of the variability properties of double-peaked emitters, especially the results of reverberation of 3C 390.3.

Because emission lines from AGN accretion disks are a tool for studying the dynamical and thermal behavior of the disk, one of our long-term goals is to pursue such studies by monitoring the variability of double-peaked emitters that we have found in this survey. Another, more lofty goal is to use the double-peaked emission lines (and their variability) to test dynamical models for the line-emitting gas in AGNs, including, for example, bipolar radial flows and the binary black hole hypothesis. The confirmation or rejection of any model for AGN broad-line regions would represent progress since the dynamics of the line-emitting gas is still poorly understood. To this end we study the general properties of double-peaked emitters and compare them with those of the average radio-loud AGN. We use these properties in combination with the profiles and relative strengths of the emission lines to assess the applicability of various proposed scenarios for the origin of the double-peaked lines. We find that the accretion disk interpretation of the line profiles is the most appealing because it provides a self-consistent framework within which all of the properties of the hosts can be understood.

Throughout this paper we adopt the following nomenclature: we refer to emission lines with double peaks or twin shoulders as double-peaked lines and to the objects that display them as double-peaked emitters. On occasion, we distinguish the subset of double-peaked lines that can be fitted well with a model of a relativistic, Keplerian disk (see §3) by referring to them as dishlike lines; their hosts are referred to as disklike emitters. We adopt a Hubble constant of \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and a deceleration parameter of \( q_0 = \frac{1}{2} \).

2. TARGETS, OBSERVATIONS, AND DATA

The target selection strategy and the motivation behind it are described in detail in Paper I. In summary, we chose to observe all moderate-redshift (\( z < 0.4 \)), radio-loud AGNs for which good H\( \alpha \) spectra were not available in the literature. The collection of targets was supplemented with objects (listed in Paper I) whose spectra were drawn from the literature. In Paper I we reported the observation of 74 broad-lined objects from the original target list, while here we present spectra of another 10 certified broad-lined objects. We also report supplementary observations of six objects whose H\( \alpha \) spectra were presented in Paper I. These observations were carried out in order to cover a broader spectral range including their broad H\( \beta \) lines and, if possible, also their narrow [O III] \( \lambda 3727 \) and broad Mg II \( \lambda 2800 \) lines. Finally, we also present spectra of three objects with double-peaked emission lines, which had been originally observed by other authors but had not been studied in detail (CBS 74, Gonçalves, Véron, & Véron-Cetty 1998; PKS 0921–213, Simpson 1994; CSO 643, Maxfield, Djorgovski, & Thompson 1995). Thus, the final collection of radio-loud, broad-lined AGNs consists of 85 objects observed by us plus 19 objects whose spectra were drawn from the literature (the spectrum of Pictor A used in Paper I was taken from the literature, while in this paper we include a spectrum obtained by us and presented in Halpern & Eracleous 1994). In the process of acquiring the data we also observed 12 objects that had only narrow emission lines and seven objects whose redshifts were higher than 0.4 (see discussion in Paper I and below). The final set of objects is not a complete sample in a statistical sense, but rather a representative collection of suitable objects in AGN catalogs, circa 1991, when the target selection was made.

The observations presented here were carried out over several observing runs using four different telescopes and spectrographs, namely, the 4 m telescope and Ritchie-Chrétien (RC) spectrograph and the 2.1 m telescope and GoldCam spectrograph at Kitt Peak National Observatory, the 4 m telescope and RC spectrograph at Cerro Tololo Inter-American Observatory, the 3 m Shane telescope and Kast double spectrograph at Lick Observatory, and the 2.4 m telescope at MDM Observatory. Most observations were carried out between 1993 and 1995, and a small number of them were carried out between 1997 and 2000. The journal of observations is given in Table 1. The spectra were taken through a narrow slit (1.5–2.0") in moderate seeing conditions (1.7–2.5"). The slit was oriented along the parallactic angle whenever necessary to avoid differential loss of light resulting from atmospheric refraction. The spectra were extracted from windows of typical width 4"–8" along the slit and were calibrated in a standard fashion as described in Paper I. The final spectral resolution was approximately 6 \( \text{Å} \) for the spectra taken with the 4 m telescopes and 3.5–4.5 \( \text{Å} \) for the spectra taken with the other telescopes.

Our collection of newly observed objects includes 13 AGNs with broad Balmer lines; their H\( \alpha \) spectra are shown in Figure 1. The remaining three newly observed objects (PKS 0511–48, 3C 381, and 3C 456) were found to have only narrow emission lines. Finally, two objects (PKS 1355–12 and PKS 2312–319) were found to have grossly incorrect cataloged redshifts; as a consequence, their H\( \alpha \) lines did not fall within the observed spectral range. The spectra of the narrow-line radio galaxies and the objects with incorrect redshifts are included in a companion paper in the Astrophysical Journal Supplement Series. That paper also includes a table of accurate redshifts of all of the objects that we have observed in our survey.

3. DEMOGRAPHY OF BROAD EMISSION LINE PROFILES

As in Paper I, we identify H\( \alpha \) profiles with displaced peaks or shoulders and divide them into groups accordingly. The noteworthy objects from this paper are 4C 31.06, Pictor A, CBS 74, PKS 0921–213, and CSO 643. Our final sample includes 106 radio-loud objects, of which 20%–23% have double-peaked Balmer lines (depending on whether or not we count objects whose double-peaked lines were known a priori). Out of a total of 24 double-peaked emitters, 17 have the blue peak stronger than the red, which has a chance probability of 0.02. Thus, there is an intrinsic
preference for the blue peak being stronger than the red, which disfavors scenarios in which a random distribution in phase space of line-emitting “clouds” gives rise to double-peaked line profiles by chance. Furthermore, 13 out of the 17 profiles that have the blue peak stronger than the red can be fitted well with a simple disk model, as we describe in later sections.

It is important to note that membership in the above groups of line profiles may be temporary, since double-peaked line profiles are known to vary significantly on timescales of years. The variations can take the form of small but significant changes in the relative strengths of the two peaks (e.g., Arp 102B; Miller & Peterson 1990; Newman et al. 1997), complete reversals in the symmetry of the profile, namely, the blue peak being stronger than the red at some epochs but not at others (e.g., 3C 590.3 and 3C 332; Zheng, Veilleux, & Grandi 1991; Gilbert et al. 1999), and the emergence of double-peaked profiles with subsequent dramatic variations (e.g., Pictor A; Halpern & Eracleous 1994; Sulentic et al. 1995; Eracleous & Halpern 1998). Therefore, the relative numbers of blue- and red-asymmetric double-peaked profiles could reflect the fraction of time that the profiles spend in a given state. For the purposes of this paper, we consider all double-peaked emitters as a group, without making a distinction based on the sense of their asymmetry or whether or not the simplest models can fit their profiles in detail.

To study the broad emission line profiles quantitatively, we measured the line widths and shifts at half-maximum and at zero intensity. The results of these measurements are listed in Table 2. The measured widths and shifts at zero intensity should be regarded with caution; their error bars (given in Table 2) are an order of magnitude larger than those on the widths and shifts at half-maximum because of the uncertainty in determining the continuum level and hence the uncertainty in identifying the far wings of the line. In Figure 2 we compare the distributions of FWHM and FWHZ of double-peaked emitters with those of other objects in our entire collection, following Paper I. The mean values and the probabilities that corresponding distributions are drawn from the same parent population (according to the Kolmogorov-Smirnov [K-S] test) are given in Table 3. The most significant difference is in the distributions of FWHM with double-peaked emitters having Hβ lines that are on average twice as broad as other objects. The distribution of fractional shifts among all objects in the collection is plotted in Figure 3, in which the double-peaked emitters are represented by the shaded histogram bins. There is a preference for redshifts, with a mean shift value of $\Delta v = 3 \times 10^4 \text{ km s}^{-1}$ (the same at half-maximum and at zero intensity, both for double-peaked emitters and for other radio-loud AGNs). In \( \frac{2}{3} \) of double-peaked emitters the Hα lines show a net redshift at half-maximum. At zero intensity the error bars are quite large, leading us to use extremely

### TABLE 1

| Object | $m_V$ | $z$ | UT Date | Exposure Time (s) | Telescope | Notes |
|--------|-------|-----|---------|-------------------|------------|-------|
| 3C 17a | 18.2  | 0.220 | 1994 Aug 5 | 1800 | Lick 3 m | Hα, Hβ, Mg II |
| 3C 456b | 18.5  | 0.233 | 1993 Dec 13 | 2000 | KPNO 4 m | (B2 0154+31A) |
| PKS 1353–12b | 16.7  | 0.276 | 1997 Jun 9 | 2700 | KPNO 2.1 m | New redshift |
| PKS 1451–37b | 16.5  | 0.053 | 1995 Mar 24 | 7200 | KPNO 4 m | Narrow lines |
| 3C 111b | 18.0  | 0.049 | 1993 Dec 13 | 3200 | KPNO 4 m | New redshift |
| PKS 1335 | 18.5  | 0.539 | 1994 Feb 15 | 2700 | KPNO 4 m | Narrow lines |
| CSO 643b | 16.7  | 0.276 | 1998 Apr 9 | 5400 | MDM 2.4 m | Hβ, Mg II |
| PKS 2247+14b | 16.9  | 0.235 | 1994 Feb 15 | 2700 | KPNO 2.1 m | Hβ, Mg II |
| PKS 1451–37b | 16.7  | 0.314 | 1994 Feb 15 | 1800 | KPNO 2.1 m | Narrow lines |
| PKS 1514+00b | 15.6  | 0.053 | 1995 Jun 4 | 3600 | KPNO 2.1 m | Narrow lines |
| 3C 351a | 15.3  | 0.372 | 1994 Jun 4 | 3600 | KPNO 2.1 m | Narrow lines |
| 3C 351a | 17.2  | 0.161 | 1994 Jul 2, 3 | 2 \times 2700 | KPNO 2.1 m | Narrow lines |
| PKS 2305+18b | 17.5  | 0.313 | 1993 Dec 12 | 1533 | KPNO 4 m | Narrow lines |
| PKS 2312–31b | 18.5  | 1.322 | 1994 Aug 5 | 1800 | KPNO 3 m | New redshift |
| 3C 456b | 18.5  | 0.233 | 1993 Dec 13 | 3600 | KPNO 4 m | Narrow lines |
| MRC 2328+167b | 18.3  | 0.280 | 1993 Dec 13 | 2400 | KPNO 4 m | Narrow lines |

*a* Repetitions from Paper I. See § 2 of the text for further details.

*b* First-time observations.

*c* Our observations of Pictor A were first reported by Halpern & Eracleous 1994.

*d* Double-peaked emitters originally found by other authors. See § 2 of the text for further details.
coarse bins. Within these large error bars there are no blueshifts among double-peaked emitters.

Our findings regarding the properties of the line profiles of the entire set of radio-loud AGNs are by no means new results. The widths and shifts we measure are in agreement with the results of more systematic and detailed studies such as those of Boroson & Green (1992), Brotherton (1996), Corbin (1995, 1997b), Sulentic et al. (1995a), and Marziani

![Fig. 1.—H\textalpha\ spectra of the 13 newly observed broad-lined objects. A list of these objects and the journal of observations are given in Table 1.](image)

**TABLE 2**

| OBJECT      | OBSERVED EW (\AA) | [O i] \((\pm20\%)\) | [S ii] \((\pm25\%)\) | STARLIGHT FRACTION (\pm0.2) | BROAD H\textalpha\ PROFILE PROPERTIES |
|-------------|-------------------|----------------------|----------------------|-----------------------------|-------------------------------------|
|             |                    |                      |                      |                             | Width (km s\textsuperscript{-1})                                      |
|             |                    |                      |                      |                             | FWZI  (\pm3000) FWHM  (\pm200) | FWZI  (\pm0.005) FWHM  (\pm0.0005) |
| MC 0041+11 | 11.9              | 4.9                  | 0.28                 |                             | 8500  4200                      | 0.0003  0.0016                          |
| 4C 31.06   | 5.4               | 23.3                 | 0.11                 |                             | 18000  9000                     | 0.0049  0.0001                          |
| 3C 111     | 7.7               | 6.3                  | 0.04                 |                             | 18400  4800                     | 0.0037  0.0001                          |
| Pictor A   | 55.7              | 30.7                 | 0.14                 |                             | 29000  18400                    | 0.0001  0.0011                          |
| CBS 74     | 7.7               | 14.4                 | 0.17                 |                             | 22100  9200                     | 0.0014  0.0003                          |
| PKS 0921–23| 5.3               | 6.2                  | 0.65                 |                             | 21900  8300                     | 0.0015  0.0002                          |
| PKS 1346–11| 4.2               | 5.2                  | 0.00                 |                             | 11500  2300                     | 0.0009  0.0003                          |
| CSO 643    | 10.1              | 26.6                 | 0.28                 |                             | 21000  9000                     | 0.0009  0.0022                          |
| PKS 1451–37| 2.6               | 4.9                  | 0.00                 |                             | 15400  3800                     | 0.0044  0.0003                          |
| PKS 1514–00| 10.8              | 15.1                 | 0.76                 |                             | 8300  4300                      | 0.0022  0.0001                          |
| PKS 2247+14| 0.0               | 4.4                  | 0.00                 |                             | 8400  3500                      | 0.0027  0.0013                          |
| PKS 2305+18| 14.6              | 15.8                 | 0.56                 |                             | 8800  4400                      | 0.0006  0.0013                          |
| PKS 2328+167| 0.0              | 6.3                  | 0.37                 |                             | 8800  3200                      | 0.0017  0.0003                          |

Note.—The uncertainty in the values of each column is given under the column heading.
It is also noteworthy that variants of many of these results have been known for more than 20 years (see Miley & Miller 1979; Steiner 1981). Our comparison of the properties of double-peaked emitters and other objects shows that double-peaked emitters are extreme objects, occupying the high end of the Balmer line width and redshift distributions. We return to these results in § 6, where we discuss them in the context of scenarios of the structure of the line-emitting region.

### 4. MODEL FITS TO DOUBLE-PEAKED PROFILES

#### 4.1. Hα Line Profiles

We have tried to fit Hα profiles with well-defined twin peaks or pronounced shoulders (4C 31.06, Pictor A, CBS 74, PKS 0921–213, and CSO 643) with the relativistic Keplerian disk model of Chen & Halpern (1989). This

### Table 3

| Quantity                        | Mean Values | K-S Probabilitya |
|---------------------------------|-------------|------------------|
| FWHM of Hα line (km s⁻¹)        | 12700       | 6200             | 2 × 10⁻⁸       |
| FWHZI of Hα line (km s⁻¹)       | 21700       | 17000            | 5 × 10⁻³       |
| Starlight fraction              | 0.33        | 0.11             | 3 × 10⁻⁵       |
| Rest EW of [O III] (Å)           | 6.8         | 5.0              | 9 × 10⁻²       |
| Rest EW of [S II] (Å)            | 12.3        | 7.7              | 1 × 10⁻³       |
| [O III]/[O II] ratio             | 0.19        | 0.07             | 7 × 10⁻²       |
| [O III]/[O II] ratio             | 0.35        | 0.21             | 9 × 10⁻²       |
| Broad Hα/Hβ ratio               | 5.23        | 4.26             | 5 × 10⁻⁴       |
| Broad Mg II/Hβ ratio            | 2.62        | 2.19             | 3 × 10⁻¹       |

a Probability that the distributions of this quantity in double-peaked emitters and in other radio-loud AGNs were drawn from the same parent population, according to the K-S test.
The outer edge of the disk is not sharp (see Chen & Halpern 1989). The disk has an axisymmetric emissivity of the form $\epsilon \propto \xi^{-q}$. Local broadening of the line is represented by a Gaussian rest-frame profile of velocity dispersion $\sigma$ (this is a combination of turbulent motions in the disk and the velocity gradient within the cells used in our numerical integration). The free parameters of the model are thus $\xi_1$, $\xi_2$, $i$, $q$, and $\sigma$. The flux illuminating the outer disk is expected to vary as $r^{-3}$, while the H$\alpha$ flux emerging from the disk is proportional to the illuminating flux for an extremely wide range of values of the latter (see Collin-Souffrin & Dumont 1989; Dumont & Collin-Souffrin 1990a, 1990b). Therefore, we adopt $q = 3$ as a reasonable prescription for the H$\alpha$ emissivity of the disk. Lower values of $q$ can result when the H$\alpha$ emissivity saturates at very high values of the ionizing flux. In Figures 4a, 4b, and 4c we show the H$\alpha$ profiles of 4C 31.06, CBS 74, and PKS 0921–213 with the best-fitting disk models superposed. The model parameters are generally in the same range as those found from fitting the double-peaked profiles of Paper I; they are summarized in Table 4. The goodness of fit was judged by eye, and the error bars on the model parameters were obtained by perturbing each parameter about its optimal value and adjusting all other parameters until an acceptable fit was no longer possible.

The above model does not describe the H$\alpha$ profiles of Pictor A and CSO 643 as well as it does those of other objects. In the case of Pictor A, the red peak is stronger than the blue, contrary to the expectations of the simplest, axisymmetric disk models, while in the case of CSO 643 an ad hoc blueshift of 1370 km s$^{-1}$ appears to be needed for a good fit. Therefore, we attempted to fit them with the elliptical disk model of Eracleous et al. (1995), which has two additional free parameters. We are not suggesting that these objects necessarily harbor eccentric accretion disks, although we do consider this a plausible scenario. The point of this exercise is to demonstrate that with some refinement, accretion disk models can account for a much wider variety of line profiles. The model parameters for these two objects

### Table 4

| Object       | $\xi_1$ (deg) | $\xi_2$ (deg) | $i$ (deg) | $q$ | $\xi_0$ (km s$^{-1}$) | $\varphi_0$ (deg) | $e$ |
|--------------|---------------|---------------|-----------|-----|-----------------------|-------------------|-----|
| H$\alpha$ Profiles |
| 3C 17 (elliptical)$^a$ | 360$^{+100}_{-40}$ | 800$^{+200}_{-200}$ | 30$^{+4}_{-3}$ | 1.7 | ...                    | 1400$^{+200}_{-200}$ | 100$^{+20}_{-20}$ | 0.3$^{+0.1}_{-0.1}$ |
| 4C 31.06...... | $>1000$ | $>14000$ | 35$^{+1}_{-1}$ | 3.0 | ...                    | 1200$^{+200}_{-200}$ | 100$^{+20}_{-20}$ | ... |
| PKS 0340–37$^a$ | 210$^{+5}_{-10}$ | 1900$^{+600}_{-600}$ | 18$^{+10}_{-1}$ | 3.0 | ...                    | 1400$^{+200}_{-200}$ | ... | ... |
| Pictor A (circular)$^b$ | 1000$^{+30}_{-10}$ | 1400$^{+200}_{-200}$ | 70$^{+20}_{-15}$ | 3.0 | ...                    | 1000$^{+200}_{-200}$ | 100$^{+30}_{-30}$ | 0.29$^{+0.26}_{-0.06}$ |
| Pictor A (elliptical)$^b$ | 220$^{+30}_{-20}$ | 550$^{+200}_{-200}$ | 30$^{+15}_{-15}$ | 1.5 | ...                    | 1000$^{+200}_{-200}$ | 100$^{+30}_{-30}$ | 0.29$^{+0.26}_{-0.06}$ |
| CBS 74............ | 170$^{+5}_{-20}$ | 1800$^{+200}_{-200}$ | 16$^{+1}_{-1}$ | 3.0 | ...                    | 1000$^{+200}_{-200}$ | 100$^{+30}_{-30}$ | ... |
| PKS 0921–213........ | $>850$ | $>5600$ | 15$^{+1}_{-1}$ | 1.5 | ...                    | 600$^{+100}_{-100}$ | ... | ... |
| PKS 1151–34$^c$ | 300$^{+100}_{-70}$ | 2000$^{+1000}_{-1000}$ | 28$^{+1}_{-1}$ | 3.0 | ...                    | 1600$^{+200}_{-200}$ | 1000$^{+30}_{-30}$ | ... |
| CSO 643 (blueshifted)$^d$ | 210$^{+40}_{-50}$ | 2000$^{+2000}_{-2000}$ | 17$^{+1}_{-1}$ | 3.0 | ...                    | 1000$^{+200}_{-200}$ | 1000$^{+30}_{-30}$ | ... |
| CSO 643 (elliptical)$^b$ | 1600$^{+800}_{-500}$ | 10000$^{+5000}_{-5000}$ | 55$^{+15}_{-15}$ | 3.0 | ...                    | 1200$^{+200}_{-200}$ | 90$^{+40}_{-40}$ | 0.5$^{+0.2}_{-0.1}$ |
| H$\beta$ Profiles |
| 3C 17 (elliptical)$^a$ | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| PKS 0340–37$^a$ | 220$^{+30}_{-20}$ | $>1500$ | ... | 5.1, 3.0 | 450$^{+100}_{-100}$ | ... | ... | ... |
| PKS 1151–34$^c$ | 400$^{+100}_{-60}$ | 2000$^{+500}_{-500}$ | ... | 5.1, 3.0 | 1000$^{+1000}_{-1000}$ | ... | ... | ... |
| CSO 643 (blueshifted)$^d$ | 210$^{+40}_{-50}$ | 2000$^{+2000}_{-2000}$ | ... | 5.1, 3.0 | 1000$^{+1000}_{-1000}$ | ... | ... | ... |
| Mg $\text{n}$ Profiles |
| 3C 17 (elliptical) | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| PKS 0340–37$^a$ | 200$^{+50}_{-20}$ | 2500$^{+500}_{-500}$ | ... | 2.2, 3.0 | 700$^{+200}_{-200}$ | ... | ... | ... |
| PKS 1151–34$^c$ | 170$^{+30}_{-20}$ | $>1500$ | ... | 2.2, 3.0 | 3000$^{+1000}_{-1000}$ | ... | ... | ... |
| CSO 643 (blueshifted)$^d$ | 200$^{+40}_{-50}$ | 3000$^{+1000}_{-1000}$ | ... | 2.2, 3.0 | 500$^{+200}_{-200}$ | ... | ... | ... |

$^a$ A single value of the emissivity power-law index is used for H$\alpha$ profiles. For H$\beta$ and Mg $\text{n}$ profiles two values of the power-law index are given, the first corresponding to the inner disk and the second to the outer disk; the transition occurs at the break radius $\xi_0$. The power-law index is generally fixed at the values predicted by photoionization models, with the exception of the H$\alpha$ profiles of 3C 17 and Pictor A (elliptical disk models) and PKS 0921–213. See the discussion in § 3 of the text.

$^b$ In the case of elliptical disk models, $\xi_1$ and $\xi_2$ are the inner and outer pericenter distances, respectively. The eccentricity of the disk increases linearly with radius, from 0 to $e$, while the major axis is oriented at an angle $\varphi_0$ to the line of sight.

$^c$ Best-fitting model parameters taken from Paper I and quoted here for reference.

$^d$ The H$\alpha$ profile of Pictor A was fitted with two different models: one of a circular disk and one of an elliptical disk (see also § 3).

$^e$ Parameters taken from Paper I, but adjusted slightly to accommodate a small variation of the profile since the earlier observation. The main change is in the value of $\sigma$.

$^f$ The H$\alpha$ profile of CSO 643 was fitted with two different models: one of a circular disk and one of an elliptical disk (see also § 3).

$^g$ Same parameters as H$\alpha$ profile.

$^h$ Same parameters as H$\alpha$ profile but with $\xi_2 > 5000$. 

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3 The effect of local broadening can be reproduced by a model in which the outer edge of the disk is not sharp (see Chen & Halpern 1989).
Fig. 4.—Fits of relativistic, Keplerian disk models to objects with double-peaked Hα lines. The model parameters are discussed in § 4.1 of the text, and their best-fitting values are given in each figure and summarized in Table 4. The objects are arranged in order of increasing right ascension. In every case the top panel shows the Hα spectrum of the object, after subtraction of the continuum, with the best-fitting model superposed (thick solid line). The bottom panel shows the residual after subtraction of the model. The dashed vertical line marks the wavelength adopted for the model profile. In (d) and (g) we show a fit of an eccentric disk model to the Hα profile of Pictor A and CSO 643, while in (f) we show a fit of a blueshifted circular disk model to the profile of CSO 643 (see § 4.1 for a detailed discussion).

(for both circular and elliptical disk models) are included in Table 4, and the fits are compared to the data in Figures 4c, 4d, 4f, and 4g. We discuss the physical justification for these models further in § 6.3.

4.2. Hβ and Mg II Line Profiles

An important prediction of the models of photoionized accretion disks by Collin-Souffrin & Dumont (1989) and
Dumont & Collin-Souffrin (1990a, 1990b) is that, because of their large densities (of order $10^{15}$ cm$^{-3}$) and column densities (of order $10^{25}$ cm$^{-2}$), the disks would emit predominantly low-ionization lines (e.g., Balmer lines, Mg II, and Fe II) rather than high-ionization lines. Thus, we have tried to verify that the profiles and strengths of the Mg II and H$\beta$ lines are consistent with an accretion disk origin using blue spectra of four objects whose Mg II lines are redshifted to wavelengths longer than the atmospheric cutoff (3C 17, PKS 0340–37, PKS 1151–34, and CSO 643; $0.2 < z < 0.3$). To carry out a more complete and detailed test, we have obtained UV spectra of several objects with relatively low redshifts ($z < 0.1$) with the Hubble Space Telescope (HST). The results for the first of these objects, Arp 102B, have been published (see §5.2), while a paper presenting our HST study of several more objects is in preparation.

According to the photoionization models we have adopted, the H$\beta$ emissivity is proportional to $r^{-3}$ at...
Fig. 5.—Broad Hα, Hβ, and Mg II profiles of 3C 17, PKS 0340–37, PKS 1151–34, and CSO 643. The profiles are plotted on a common velocity scale, and the best-fitting disk model profiles are superposed for comparison. The model parameters are summarized in Table 4. In the case of 3C 17 and CSO 643, the model superposed on Hβ is a scaled version of the model that was tuned to fit Hα.
moderate radii, but it rises steeply toward the center at small radii (approximately as \( r^{-3} \)). The Mg \( \text{II} \) line emissivity is also proportional to \( r^{-3} \) at moderate radii and becomes "shallow" at small radii. The emissivity of all lines saturates at very high incident fluxes (i.e., at very small disk radii); the incident flux required to saturate H\( \alpha \) is about an order of magnitude higher than that for H\( \beta \) or Mg \( \text{II} \). The emissivity laws described above are summarized in Figure 7 of Collin-Souffrin & Dumont (1989). Thus, we parameterized the disk emissivity as a broken power law of the form
\[
\epsilon(\xi) = \begin{cases} 
\epsilon_0 \xi^{\alpha \gamma - \eta}, & \text{for } \xi_1 < \xi < \xi_2 \\
\epsilon_0 \eta \xi^{\eta - \eta}, & \text{for } \xi_2 < \xi < \xi_0 
\end{cases}
\] (1)
where \( \epsilon_0 \) is a constant of proportionality, \( \xi_0 \) is the break radius at which the power-law index changes, and the factor \( \xi_0^{\alpha \gamma - \eta} \) ensures that the emissivity is continuous at \( \xi_0 \). The power-law indices were held fixed to \( q_1 = 5.1 \) and \( q_2 = 3 \) for the H\( \beta \) fit. For the Mg \( \text{II} \) fit we set \( q_2 = 3 \) and allowed \( q_1 \) to vary between 2 and 3 to simulate the flattening of the emissivity profile at small radii. The broadening parameter, \( \sigma \), and of course the inclination angle of the disk, \( i \), were held fixed to the values determined by fitting the H\( \alpha \) profile in Paper I. We also tried to keep the inner and outer radii of the line-emitting disk close to the values determined from fitting H\( \alpha \), although this was not always possible (the parameters determined from fits to the H\( \alpha \) profiles are more robust because the H\( \alpha \) profile is not seriously contaminated by strong, narrow lines and has the simplest emissivity law).

Figure 5 shows a montage of the H\( \alpha \), H\( \beta \), and Mg \( \text{II} \) profiles for each of the three objects, plotted on a common velocity scale, with the best-fitting models superposed. The model parameters are summarized in Table 4. In the case of 3C 17 we used an elliptical disk model to describe the line profile (see § 4.1); the model for the H\( \alpha \) line also describes the low signal-to-noise ratio (S/N) profile of the weak H\( \beta \) line. In the case of CSO 643 we applied a blueshift of 1370 km s\(^{-1}\) to the model profiles (see §§ 4.1 and 6.3).

We find that the model parameters expected on theoretical grounds produce acceptable fits to the H\( \beta \) profiles. However, the goodness of fit can be judged only for the blue half of the line profile because the red side is overwhelmed by the very strong [O \( \text{III} \)] \( \lambda \lambda 4959, 5007 \) doublet from the narrow-line region. As a result, we cannot easily distinguish between a simple and a broken power-law emissivity prescription for the H\( \beta \) line. The observed Mg \( \text{II} \) profiles are also consistent with a disk origin, although they appear to come from a larger region of the disk than what we expected on theoretical grounds. In fact, in some cases we can obtain only a lower limit to the outer radius of the Mg \( \text{II} \)-emitting region of the disk.

The relative strengths of the H\( \alpha \), H\( \beta \), and Mg \( \text{II} \) lines of the four objects were measured by integrating the flux in the best-fitting models, and they are included in Table 5. This table also includes the H\( \alpha \)/H\( \beta \) ratios of all other double-peaked emitters for which the H\( \beta \) lines have been observed and the Mg \( \text{II} \)/H\( \beta \) ratio for Arp 102B from Halpern et al. (1996); these ratios were measured by superposing the two profiles and scaling them so that they matched. All line ratios have been corrected for reddening in the interstellar medium of the Galaxy (see § 5.1). We find that the measured H\( \alpha \)/H\( \beta \) ratios are generally consistent with the predictions of Dumont & Collin-Souffrin (1990a), but the measured Mg \( \text{II} \)/H\( \beta \) ratios are higher than the model predictions by a factor of about 3. The discrepancy can be the result of one or a combination of the following effects:

1. The disk is not the only source of Mg \( \text{II} \) emission; a wind overlaying the geometrically thin disk may contribute significantly to the observed Mg \( \text{II} \) flux but not to the observed H\( \beta \) flux. The profile of the Mg \( \text{II} \) line from the wind is likely to be narrower than that from the disk and single peaked, and it could fill in the trough between the two peaks of the disk profile. Thus, the situation would be analogous to the H\( \alpha \) lines of Arp 102B, where there is strong evidence that the line profiles comprise contributions from two different sources with different dynamics and ionization structure (Halpern et al. 1996).

2. The ionizing flux intercepted by the disk is so low that the metal lines are formed primarily by collisional excitation rather than recombination, while the Balmer lines are formed almost exclusively by recombination. This effect is discussed by Collin-Souffrin & Dumont (1989) and reiterated by Dumont & Collin-Souffrin (1990a). These authors note that such an effect is an important characteristic of weakly ionized media. Thus, the Mg \( \text{II} \)/H\( \alpha \) ratio rises above unity in the outer disk, with the consequence that the outer disk makes a significant contribution to the Mg \( \text{II} \) line but not to the H\( \alpha \) line. This behavior is not captured by the simple power-law parameterization that we have adopted.

Our overall conclusion is that the photoionization models of Collin-Souffrin & Dumont (1989) and Dumont & Collin-Souffrin (1990a, 1990b) fare moderately well against the observations. They provide emissivity prescriptions that can be used to fit the observed line profiles well, and they can predict the H\( \alpha \)/H\( \beta \) ratios fairly well. We note in closing that as more observations of Mg \( \text{II} \) lines become available, tests of these models can be refined and extended.

5. OBSERVATIONAL PROPERTIES OF DOUBLE-PEAKED EMITTERS

5.1. Optical Spectroscopic Properties and Evaluation of Extinction

Following Paper I, we repeat and refine the statistical comparisons between the starlight fraction and narrow-line equivalent widths (EWs) of double-peaked emitters using the combined data from both papers. We also compare the distribution of the ratios of the narrow oxygen lines, [O \( \text{I} \)]/[O \( \text{II} \)] and [O \( \text{II} \)]/[O \( \text{III} \)], of double-peaked emitters and other radio-loud AGNs. These line ratios serve as a diagnostic of the ionization state of the narrow-line region. Unlike Paper I, we put all double-peaked emitters in the same group, without distinguishing objects whose H\( \alpha \) profiles are well described by a disk model (see our discussion in § 3).

In Table 2 we list the observed EWs of the [O \( \text{I} \)] and [S \( \text{II} \)] lines and the fractional contribution of starlight to the optical continuum around H\( \alpha \) in the newly observed objects. In Table 5 we list the oxygen line ratios of double-peaked emitters and comparison objects, which were either measured from our own spectra or drawn from a number of sources in the literature. The effects of Galactic reddening were corrected using the reddening measurements of Schlegel, Finkbeiner, & Davis (1998) and assuming the Seaton (1979) reddening law. To guard against uncertainties in the absolute flux calibration of any individual spectrum, line ratios were computed only if both lines could be measured from the same spectrum. We were able to match the redshift
### Table 5

**Emission-Line Ratios**

| Object | [O I]/[O III] | [O I]/[O III] | Hα/Hβ | Mg II/Hβ | References |
|--------|--------------|--------------|--------|----------|------------|
|        | Double-peaked Emitters | Other Radio-loud AGNs |        |          |            |
| 3C 17  | 0.43         | 0.74         | 7.19a  | 1.34a    | 1          |
| 4C 31.06 | 0.048         | 0.40         | 4.90   | ...      | 1          |
| 3C 59   | 0.066        | 0.15         | 4.64   | ...      | 2          |
| IRAS 0236.6—3101 | 0.10         | ...         | ...    | ...      | 1, 3       |
| PKS 0340—37 | 0.083        | 0.27         | 5.28   | 1.91     | 1          |
| 3C 93   | 0.055        | 0.26         | 4.38   | ...      | 1          |
| MS 0450.3—1817 | 0.46         | 0.70         | ...    | ...      | 1          |
| Pictor A | 0.58         | 0.50         | 6.65   | ...      | 1          |
| B2 0742+31 | 0.028        | ...         | 5.16   | ...      | 1          |
| CBS 74  | 0.087        | 0.18         | 3.00   | ...      | 1          |
| PKS 0857—19 | 0.16         | ...         | 4.78   | ...      | 1          |
| PKS 0921—213 | 0.22        | 0.11         | 4.59   | ...      | 1          |
| 4C 36.18 | 0.11         | 0.22         | 5.63   | ...      | 1          |
| PKS 1151—34 | 0.10        | 0.33         | 7.32   | 4.06     | 1          |
| CSO 643 | 0.071        | 1.2          | 4.41   | 1.83     | 4          |
| 3C 332  | 0.14         | 0.16         | 7.38   | ...      | 3          |
| Arp 102B | 0.78         | 1.2          | 4.41   | 1.83     | 4          |
| PKS 1739+18C | 0.15        | ...         | 5.27   | ...      | 1          |
| 3C 382  | 0.070        | 0.15         | 4.82   | ...      | 5          |
| 3C 390.3 | 0.064        | 0.070        | 5.84   | ...      | 5          |
| PKS 1914—45 | 0.12        | ...         | 5.10   | ...      | 1          |

**References**

1. [Reference 1](#)
2. [Reference 2](#)
3. [Reference 3](#)
4. [Reference 4](#)
5. [Reference 5](#)
6. [Reference 6](#)
range of the \([\text{O} \text{ i}]/[\text{O} \text{ iii}]\) comparison sample to that of the double-peaked emitters (i.e., \(z < 0.4\)). In the case of the \([\text{O} \text{ ii}]/[\text{O} \text{ iii}]\) comparison sample, however, we had to extend the redshift range to \(z < 0.6\) so as to build up a sizable sample from published data.

The results of these comparisons are shown graphically, in the form of histograms in Figures 6 and 7. The average values of the relevant quantities are summarized in Table 3 along with the probability that their distributions in double-peaked emitters and other radio-loud AGNs were drawn from the same parent population. The results of this comparison reaffirm the conclusions of Paper I: the mean starlight fraction in double-peaked emitters is 3 times higher than in other radio-loud AGNs, while the mean rest-frame EWs of the \([\text{O} \text{ i}]\) and \([\text{S} \text{ ii}]\) lines are 36% and 60% higher, respectively. The oxygen line ratios suggest that the narrow-line regions of double-peaked emitters are at a lower ionization state than those of typical radio-loud AGNs. The oxygen line ratios of double-peaked emitters, are, in fact, reminiscent of low-ionization nuclear emission-line regions (LINERs); after Heckman (1980), although only Arp 102B fulfills the formal definition of that class. We discuss this connection further in our interpretation of the properties of double-peaked emitters in §6.1.

In addition to the properties of the narrow lines, we have also studied the properties of the broad lines of

**TABLE 5—Continued**

| OBJECT | \([\text{O} \text{ i}]/[\text{O} \text{ iii}]\) | \([\text{O} \text{ ii}]/[\text{O} \text{ iii}]\) | H\(\alpha)/H\(\beta\) | Mg \(\text{ii}/H\(\beta\) | REFERENCES |
|--------|-----------------|-----------------|-----------------|-----------------|------------|
| PKS 1355−41 | 0.13 | 0.13 | 4.53 | \ldots | 1, 6, 8 |
| Mrk 668 | 0.036 | \ldots | \ldots | \ldots | 1 |
| PKS 1417−19 | 0.033 | 0.046 | 4.83 | \ldots | 2 |
| PKS 1421−38 | 0.066 | \ldots | 3.54 | \ldots | 1 |
| B2 1425+26 | 0.074 | \ldots | 6.64 | \ldots | 16 |
| PKS 1451−37 | 0.040 | \ldots | 4.04 | \ldots | 1 |
| 4C 69.18 | 0.063 | \ldots | 4.14 | \ldots | 16 |
| PKS 1510−08 | \ldots | 0.17 | \ldots | 2.23 | 1, 6, 8 |
| 4C 37.43 | 0.028 | \ldots | 4.21 | \ldots | 1 |
| PKS 1514+00 | 0.50 | 1.2 | \ldots | \ldots | 1 |
| LB 9743 | 0.007 | \ldots | 4.19 | \ldots | 16 |
| 3C 323.1 | 0.025 | \ldots | 2.98 | 1.80 | 10, 16 |
| 3C 334 | \ldots | \ldots | \ldots | 2.70 | 10 |
| 3C 345 | \ldots | \ldots | \ldots | 3.00 | 10 |
| 4C 18.47 | \ldots | \ldots | 3.75 | \ldots | 16 |
| 4C 61.34 | \ldots | 0.69 | \ldots | \ldots | 7 |
| 3C 351 | 0.015 | 0.087 | \ldots | 1.97 | 8 |
| B2 1719+35 | 0.059 | \ldots | 3.45 | \ldots | 1, 16 |
| 4C 34.47 | 0.070 | 0.058 | 4.44 | 2.58 | 8 |
| PKS 1725+04 | 0.030 | \ldots | 3.42 | \ldots | 16 |
| MRC 1745+16 | 0.043 | \ldots | 3.93 | \ldots | 1 |
| 3C 381 | 0.053 | 0.23 | \ldots | \ldots | 2 |
| 4C 73.18 | 0.030 | \ldots | 3.87 | \ldots | 7, 8 |
| PKS 2128−12 | \ldots | 0.088 | \ldots | \ldots | 6 |
| PKS 2135−14 | 0.092 | 0.090 | 4.48 | \ldots | 6, 16 |
| PKS 2140−04 | 0.054 | \ldots | 3.33 | \ldots | 1 |
| OX 169 | 0.025 | \ldots | 3.23 | \ldots | 1, 7 |
| 4C 31.63 | \ldots | \ldots | 3.48 | 2.30 | 7, 10 |
| PKS 2208−13 | 0.071 | \ldots | 3.90 | \ldots | 1 |
| 3C 445 | 0.042 | 0.078 | 6.63 | \ldots | 5 |
| PKS 2227−39 | 0.058 | \ldots | \ldots | \ldots | 1 |
| PKS 2247+14 | 0.018 | \ldots | 5.00 | \ldots | 1 |
| 4C 11.72 | \ldots | 0.13 | 4.90 | 1.00 | 7, 10 |
| PKS 2302−71 | 0.046 | \ldots | 3.93 | \ldots | 1 |
| PKS 2305+18 | 0.046 | \ldots | 3.98 | \ldots | 1, 16 |
| PKS 2345−167 | \ldots | 0.20 | \ldots | 4.55 | \ldots | 7 |
| PKS 2349−01 | 0.038 | 0.28 | 4.07 | \ldots | 2 |

**Notes.**—Table 5 is also available in machine-readable form in the electronic edition of the *Astrophysical Journal*. All objects have redshifts less than 0.6. Line ratios have been corrected for Galactic reddening using the Seaton 1979 law and the color excess reported by Schlegel et al. 1998. Uncertainties on line ratios from this work and from Paper I are typically 20%.

(a) The H\(\alpha)/H\(\beta\) and Mg \(\text{ii}/H\(\beta\) ratios of 3C 17 are fairly uncertain because of the weakness of H\(\beta\). The H\(\alpha)/Mg \(\text{ii}\) ratio, however, is not as uncertain; its value is 5.36.

(b) The reported line ratio refers to the total flux of the broad and narrow lines combined.

**References.**—(1) Eracleous & Halpern 1994; this paper. (2) Grandi & Osterbrock 1978. (3) Colina, Lipari, & Machetto 1991. (4) Halpern et al. 1996. (5) Osterbrock, Koski, & Phillips 1976. (6) Tadhunter et al. 1993. (7) Jackson & Browne 1991a. (8) Grandi & Phillips 1979. (9) Thuan, Oke, & Bergeron 1979. (10) Wills et al. 1995; M. S. Brotherton & B. J. Wills 1996, private communication. (11) Gelderman & Whittle 1994. (12) Osterbrock 1977. (13) Phillips 1978. (14) Baldwin 1975. (15) Wills et al. 1993. (16) Jackson & Eracleous 1995.
double-peaked emitters using a similar approach. In Table 5 we list the Hα/Hβ and Mg ii/Hβ ratios of double-peaked emitters and comparison objects. Measurements, reddening corrections, and construction of comparison samples were carried out as for the narrow-line ratios (including extension of the redshift range of the Mg ii/Hβ comparison sample to z < 0.6). The Mg ii/Hβ ratios for many of the comparison objects were kindly provided by M. S. Brotherton and B. J. Willis. In Figure 7 we compare the distributions of broad-line ratios in double-peaked emitters and in other radio-loud AGNs, while the mean values and K-S probabilities are included in Table 3. We find that the distributions of the Hα/Hβ ratio are considerably different, while those of the Mg ii/Hβ ratio are quite similar, although this is based on a small number of double-peaked emitters. At first glance, one can interpret the larger Hα/Hβ ratio of double-peaked emitters as the result of reddening, which would imply a difference in the mean extinction in the two groups of about ∆A_V ≈ 0.35. However, this interpretation would be in conflict with the Mg ii/Hβ ratios of double-peaked emitters, which are not accordingly smaller than those of the comparison objects. Since this statement is based only on a small number of measurements of the Mg ii/Hβ ratio in double-peaked emitters, it should be checked again as more data become available. If we take the Mg ii/Hβ distributions at face value, we conclude that the broad-line regions of disk-like emitters are not unusually reddened. Rather, it is more plausible that the Hα/Hβ ratios of double-peaked emitters are enhanced by collisional excitation, which could be a consequence of an origin of the broad Balmer and Mg ii lines in the dense material of an accretion disk.

5.2. Properties at Other Wavelengths

All of the double-peaked emitters considered here are radio-loud. The radio properties of the entire set (5 GHz monochromatic luminosities, spectral indices, and morphologies) are listed in Table 6. Most double-peaked emitters are powerful FR II radio galaxies (Fanaroff & Riley 1974) with L_{5 GHz} ≥ 10^{25} W Hz^{-1} and double-lobed radio morphologies; three objects are associated with powerful but compact steep-spectrum radio sources. Four objects (IRAS 0236.6–3101, 1E 0450.3–1817, PKS 0921–213, and Arp 102B) have L_{5 GHz} ≤ 10^{23} W Hz^{-1}, which is intermediate between what are commonly considered high and low radio luminosities.

The infrared properties of double-peaked emitters are poorly known. Only two of the nearest and best studied objects have been detected by IRAS: Arp 102B and 3C 390.3. In the broadband spectral energy distributions (SEDs) of these two objects (Chen et al. 1989; Golombek, Miley, & Neugebauer 1988) the usual “UV bump” is absent. Instead, these SEDs peak in the infrared band around 25 μm. The weakness of the nonstellar continuum in the optical spectra of all double-peaked emitters is probably a manifestation of the absence of a UV bump. The UV spectra of double-peaked emitters can afford important tests of models for the origin of the double-peaked lines via the strong, high-ionization resonance lines that they cover. The only double-peaked emitter with a published UV spectrum from the HST (i.e., with a moderate resolution and a high S/N) is Arp 102B (Halpern et al. 1996). This spectrum shows that Mg ii is the only UV line that is as broad as the Balmer lines and that the twin peaks of the low-ionization lines do not have counterparts in the high-ionization lines. The upper limit to the Lyα/Hβ ratio in the twin peaks is 0.15. The absence of a double-peaked Lyα line cannot be the result of reddening because this would be in conflict with the observed Mg ii/Hβ and Hα/Hβ ratios that are typical of radio-loud AGNs (see § 5.1). We discuss the implications of this spectrum further in § 6.2. We are currently in the process of analyzing HST spectra of more double-peaked emitters.

A fair fraction of double-peaked emitters are bright enough in the X-ray band to allow their X-ray properties to be studied. Soft X-ray fluxes of most double-peaked emitters are listed in Table 7, which is an expanded and updated version of a similar table from Paper I. The hard X-ray spectra of many of the nearby double-peaked emitters have been studied with ASCA (0.5–10 keV; see, for example, Wozniak et al. 1998; Sambruna, Eracleous, & Mushotzky 1999) and RXT (4–100 keV; see Eracleous, Sambruna, & Mushotzky 2000 and references therein). The general conclusion is that...
the X-ray spectra of most double-peaked emitters do not differ from those of typical radio-loud AGNs.

6. DISCUSSION
6.1. Interpretation of the Properties of Double-peaked Emitters

The accretion disk model of Chen et al. (1989) and Chen & Halpern (1989) can provide an explanation for the unusual properties of double-peaked emitters. The predicted line profiles can fit the data, and the model also provides a self-consistent framework within which the other observational properties of this group of objects can be understood. Motivated by the need to balance the energy budget of the outer, line-emitting part of the disk, Chen & Halpern (1989) proposed that the inner accretion disk is a vertically extended structure that can illuminate the outer disk effectively and power the line emission. The energy budget problem comes about because the Hα luminosity is uncomfortably close to, or in some cases in excess of, the power dissipated by viscous stresses in the line-emitting portion of the disk. This power deficit is demonstrated in Fig. 7.

Fig. 7.—Distributions of the narrow [O i]/[O iii] and [O ii]/[O iii] ratios and the broad Hα/Hβ and Mg ii/Hβ ratios. The top panel in each pair shows the distribution of the corresponding line ratio in double-peaked emitters, while the bottom panel shows the distribution of the same ratio in the comparison sample. All line ratios have been corrected for Galactic reddening. The values are tabulated in Table 5.
Table 6 (an updated version of Table 9 of Paper I) and in Figure 8, where we compare their H\textalpha luminosities with the power output of their line-emitting disks. The power output of the disk was computed using equation (4) of Paper I and the X-ray luminosity, under the assumption that the X-ray luminosity represents 1% of the available accretion power. In 30% of the cases the H\textalpha luminosity is higher than the local power output of the line-emitting portion of the disk, and in 90% of the cases this fraction is more than 0.1 (Fig. 8a). On the other hand, the soft X-ray luminosity always exceeds the H\textalpha luminosity (their ratio is more than 10 in 70% of the cases). This comparison suggests very strongly that the Balmer lines are powered by photoionization of the outer disk by radiation produced in the inner disk.

The inner accretion disk was hypothesized by Chen & Halpern (1989) to be a hot, ion-supported torus (Rees et al. 1982) that radiates the available accretion power inefficiently, and its existence is favored at low accretion rates (1–2 orders of magnitude below the Eddington rate). The preferential association of double-peaked emitters with radio-loud AGNs was also explained automatically, since the original ion torus model was intended to explain the formation of radio jets. The inner radius of the line-emitting part of the disk was, therefore, identified with the radius at which the disk puffs up to form the torus, while the outer radius was identified with the radius at which the disk fragments into discrete, self-gravitating clouds. The structure and properties of the ion torus are very similar to those of advection-dominated or convection-dominated accretion

| Object          | $L_{5\text{GHz}}$ (W Hz$^{-1}$) | $s^a$ | Morphology                      | References |
|-----------------|-------------------------------|------|---------------------------------|------------|
| 3C 17           | $6.5 \times 10^{26}$          | 0.62 | Fragmented lobes + core         | 1          |
| 4C 31.06        | $2.8 \times 10^{26}$          | 0.70 | Extended to 90 kpc (presumably lobes) | 2, 3, 4    |
| 3C 59           | $4.7 \times 10^{25}$          | 0.72 | Twin lobes + compact core       | 5          |
| PKS 0235+025    | $3.8 \times 10^{25}$          | 0.72 | Twin lobes + compact core       | 6          |
| IRAS 0236–3101  | $6.0 \times 10^{22}$          | ...  | ...                             | 7          |
| PKS 0340–37     | $2.8 \times 10^{26}$          | 0.87 | Core with extension (low-resolution map) | 8          |
| 3C 93           | $6.0 \times 10^{26}$          | 0.93 | Twin lobes                      | 9          |
| MS 0450–3–1817  | $4.1 \times 10^{23}$          | ...  | Possible lobes + core           | 10, 11     |
| Pictor A        | $8.5 \times 10^{25}$          | 1.07 | Edge-brightened double lobes    | 1, 12      |
| B2 0742+31      | $1.1 \times 10^{27}$          | 0.82 | Twin lobes + compact core       | 3, 13      |
| CBS 74          | $1.3 \times 10^{25b}$         | ...  | ...                             | 8, 13, 14  |
| PKS 0857–19     | $2.7 \times 10^{26}$          | 0.80 | Twin lobes + compact core       | 15         |
| PKS 0921–213    | $4.4 \times 10^{24}$          | 0.66 | Twin lobes + compact core       | 8, 15, 16  |
| PKS 1020–103    | $2.0 \times 10^{25}$          | 0.92 | Faint lobes + compact core      | 17         |
| 4C 36.18        | $1.7 \times 10^{26}$          | 0.95 | Twin lobes                      | 3, 18      |
| PKS 1151–34     | $9.5 \times 10^{26}$          | 0.76 | Compact                         | 1, 19      |
| TXS 1156+213    | $5.0 \times 10^{25}$          | 0.78 | ...                             | 3          |
| CSO 643         | $8.3 \times 10^{25}$          | 0.62 | Asymmetric lobes + compact core | 8, 13      |
| 3C 303          | $8.9 \times 10^{25}$          | 0.81 | Twin lobes + compact core       | 20         |
| 3C 332          | $9.0 \times 10^{25}$          | 0.92 | Twin lobes + compact core       | 5          |
| Arp 102B        | $2.4 \times 10^{23}$          | 0.22 | Compact with extended halo      | 21         |
| PKS 1739+18C    | $5.6 \times 10^{25}$          | 0.83 | Twin lobes + faint core         | 3, 8, 17   |
| 3C 382          | $3.4 \times 10^{25}$          | 0.67 | Twin lobes + compact core       | 5          |
| 3C 390.3        | $6.3 \times 10^{25}$          | 0.62 | Twin lobes + compact core       | 20         |
| PKS 1914–45     | $2.3 \times 10^{26}$          | 0.94 | ...                             | 22         |
| PKS 2300–18     | $5.8 \times 10^{25}$          | 0.77 | Asymmetric lobes + compact core | 15, 19     |

Table 7 (an updated version of Table 9 of Paper I) and in Figure 8, where we compare their H\textalpha luminosities with the power output of their line-emitting disks. The power output of the disk was computed using equation (4) of Paper I and the X-ray luminosity, under the assumption that the X-ray luminosity represents 1% of the available accretion power. In 30% of the cases the H\textalpha luminosity is higher than the local power output of the line-emitting portion of the disk, and in 90% of the cases this fraction is more than 0.1 (Fig. 8a). On the other hand, the soft X-ray luminosity always exceeds the H\textalpha luminosity (their ratio is more than 10 in 70% of the cases). This comparison suggests very strongly that the Balmer lines are powered by photoionization of the outer disk by radiation produced in the inner disk.

The inner accretion disk was hypothesized by Chen & Halpern (1989) to be a hot, ion-supported torus (Rees et al. 1982) that radiates the available accretion power inefficiently, and its existence is favored at low accretion rates (1–2 orders of magnitude below the Eddington rate). The preferential association of double-peaked emitters with radio-loud AGNs was also explained automatically, since the original ion torus model was intended to explain the formation of radio jets. The inner radius of the line-emitting part of the disk was, therefore, identified with the radius at which the disk puffs up to form the torus, while the outer

![Fig. 8.—Distribution of (a) the ratio of the accretion power available in the line-emitting portion of the accretion disk to the H\textalpha luminosity ($W_{\text{disk}}/L_{\text{H\alpha}}$) and (b) the ratio of the X-ray luminosity to the H\textalpha luminosity ($L_x/L_{\text{H\alpha}}$). Notice that $W_{\text{disk}}/L_{\text{H\alpha}} < 1$ in 30% of the cases and $W_{\text{disk}}/L_{\text{H\alpha}} < 10$ in 90% of the cases.](image)
flows (ADAFs and CDAFs, possibly accompanied by an outflow) discussed more recently by many authors, including Narayan & Yi (1994, 1995), Blandford & Begelman (1999), Igumenchev & Abramowicz (1999, 2000), and Narayan, Igumenchev, & Abramowicz (2000).4

The SED of an ion torus is relatively hard, lacking a UV bump (the hallmark of a geometrically thin accretion disk), having instead a shape that resembles a power law in the UV and soft X-ray bands and a peak in the far-IR, between 30 and 300 μm (see, for example, Di Matteo et al. 1999, 2000; Ball, Narayan, & Quataert 2001). Such an SED explains the weakness of the nonstellar continuum in the optical spectra of double-peaked emitters in general. Moreover, the IR peak in the SEDs of Arp 102B and 3C 390.3 can be identified with the peak predicted by emission models for an ion torus. The unusually low ionization state of the narrow-line regions of double-peaked emitters (see § 5.1) can also be understood in this context and with the help of photoionization models for LINERs (Halpern & Steiner 1983; Ferland & Netzer 1983). These models show that an otherwise “normal” narrow-line region, illuminated by an ionizing continuum with a power-law spectrum and a low ionization parameter, produces emission lines with relative strengths very similar to what is observed in double-peaked emitters. More recent photoionization calculations, carried out by Nagao et al. (2002) and intended specifically for double-peaked emitters, reach the same conclusion. In particular, Nagao et al. (2002) have compared the narrow-line ratios of double-peaked emitters and of a large collection of other radio-loud AGNs with photoionization models employing two different SEDs: one consisting of a simple power law and one including a UV bump. They find that the narrow-line ratios of double-peaked emitters are best explained by models with a power-law SED.

6.2. Further Tests of the Accretion Disk Interpretation

The origin of the broad, double-peaked Balmer lines in an accretion disk is supported further by tests on two of the best studied objects, Arp 102B and 3C 390.3, which we describe below.

In the case of Arp 102B, the profile of the Lyα line is single peaked, bell shaped, and considerably narrower than those of the double-peaked Balmer lines (see Fig. 3 of Halpern et al. 1996). The best interpretation of this difference is that the region producing the double-peaked Balmer lines has such a high density and column density (n ~ 10^{15} cm^{-3} and N_H ~ 10^{25} cm^{-2}) that the Lyα photons it produces are trapped by resonance scattering and destroyed by collisional de-excitation. In fact, this dramatic difference in line profiles was predicted by Rokaki, Boisson, & Collin-Souffrin (1992) based on the accretion disk photoionization models of Collin-Souffrin & Dumont (1989).

A reverberation mapping campaign of 3C 390.3 by the International AGN Watch (Dietrich et al. 1998; O’Brien et al. 1998) has shown that the Balmer lines respond to variations of the continuum with a lag of 20 days and that the blue and red sides of the line respond together with an upper

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4We use the term “ion torus” throughout to denote a generic hot, vertically extended, optically thin, and radiatively inefficient accretion flow. These general properties, rather than the exact structure of the flow, are what is important to our interpretation.
limit on the delay between them of 4 days. Similar results were obtained by Sergeev et al. (2002), who also estimated the transfer function of the Hα line of 3C 390.3 and found it to peak sharply at a lag of 60 days. This is exactly the behavior that one would expect from an accretion disk, as noted by Gaskell (1999). Moreover, Sergeev, Pronik, & Sergeeva (2000) find the same behavior in Arp 102B, with the broad Hα line lagging the continuum variations by less than 66 days. Estimates of the mass of the central black hole in 3C 390.3 from reverberation mapping range from 3 × 10^8 (Peterson & Wandel 2000) to 2 × 10^9 M☉ (Sergeev et al. 2002).

Finally, we note a reassuring consistency check based on the superluminal motion observed in the radio core of 3C 390.3 by Alef et al. (1994, 1996). The combination of a number of constraints on the orientation of the radio jet yields an inclination angle of the jet of 19°–42° (Eracleous, Halpern, & Livio 1996). This is in good agreement with the inclination angle of the axis of the accretion disk of 26° ± 4° deg obtained in Paper I by fitting the Hβ profile.

The observations described in this section also serve as tests of alternative scenarios for the origin of double-peaked lines, which we discuss in later sections.

6.3. Discussion of Individual Objects: Pictor A and CSO 643

In § 4.1 we noted that the simplest, axisymmetric disk model does not describe the Hα profiles of Pictor A and CSO 643 extremely well, which led us to use more sophisticated models. Here we describe the physical motivation for the models that we used.

**Pictor A.**—The double-peaked lines appeared some time between 1983 and 1989. A spectrum taken in 1983 by Filippenko (1985) shows a single-peaked Hα line with very broad wings, while spectra taken between 1989 and 1994 (Halpern & Eracleous 1994; Sulentic et al. 1995b) show the Hα line to be double peaked and quite variable. Halpern & Eracleous (1994) speculated that the appearance of the double-peaked line was related to a major structural change in the accretion disk, while Sulentic et al. (1995b) attributed the double-peaked lines to a bipolar outflow. An important feature of the Hα profile of Pictor A is that the red peak is stronger than the blue (at least at the time that our spectrum was taken), contrary to the prediction of the simplest disk models. This feature, however, does not preclude the origin of the line in an accretion disk. Any departure of the disk from axisymmetry will lead to line profiles that differ from those predicted by the simplest models. Specific examples of nonaxisymmetric disks include (but are not limited to) disks with spiral waves (Chakrabarti & Wiita 1994), eccentric disks (Eracleous et al. 1995), and disks with warps induced by intense irradiation (Pringle 1996; Maloney, Begelman, & Pringle 1996). In fact, the dynamical signatures of the first two of these examples of nonaxisymmetric disks have been detected in cataclysmic variables (Steeghs, Harlaftis, & Horne 1997; Baptista & Catalán 2000; Patterson, Halpern, & Shemmer 1993). Refining the simplest disk model by introducing an eccentricity allows us to fit the Hβ profile of Pictor A, as illustrated in Figure 4c. Such departures from

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Eracleous et al. (1996) used the observed superluminal speed to derive an upper limit on the jet inclination angle of 33°. Under the assumption that H0 = 50 km s⁻¹ Mpc⁻¹, if we take H0 = 70 km s⁻¹ Mpc⁻¹, we obtain an upper limit of 42° on the jet inclination angle.

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the simplest model are not uncommon, as shown by Eracleous et al. (1995). We must also note that the Hα profile of Pictor A has been varying dramatically over the past decade (see the sequence of spectra presented by Eracleous & Halpern 1998), which means that the particular models that we discuss here are at best applicable to a single epoch.

**CSO 643.**—The double-peaked Hα profile of CSO 643 resembles those of 3C 59, PKS 0340−37, and CBS 74: they all have a pronounced red shoulder, which is much more extended than the blue one, and require small inclination angles (i < 20°) for a good fit. However, in CSO 643 the net redshift of the entire profile is smaller than in the other objects, preventing us from obtaining a good fit with a simple circular disk model. There are two ways to improve the fit: (1) We can apply an ad hoc blueshift to the model of 1370 km s⁻¹. The best-fitting circular disk model found under this assumption is shown in Figure 4e overlayed on the observed profile. The model parameters are summarized in Table 4. (2) We can use a more sophisticated model with more free parameters, such as an elliptical disk model (Eracleous et al. 1995). The best-fitting model of this type is shown in Figure 4g, and the model parameters are summarized in Table 4.

Either of the above modifications to the simple disk model can be physically justified by appealing to the effects of an unseen supermassive companion to the accreting black hole. In case 1 the blueshift is a result of the orbital motion of the accreting black hole around the center of mass of the supermassive binary. In case 2 the eccentricity of the hypothesized elliptical disk is excited by the tidal effect of the unseen companion (see the discussion in Eracleous et al. 1995 and references therein).

6.4. Alternative but Less Appealing Scenarios for Double-peaked Lines

In addition to accretion disk emission, three other scenarios have been suggested for the origin of double-peaked emission lines, namely, (1) emission from a binary broad-line region associated with a supermassive binary black hole, (2) emission from the oppositely directed sides of a bipolar outflow, and (3) emission from a spherically symmetric broad-line region illuminated by an anisotropic source of ionizing radiation. In this section we describe these scenarios and evaluate them in light of the currently available data. We consider all of the observational consequences of each scenario and assess it based on how well it can explain the observational properties of double-peaked emitters.

6.4.1. Binary Broad-Line Region

The idea that supermassive binary black holes (resulting from the merger of their parent galaxies) reside in the nuclei of radio-loud AGNs was suggested by Begelman, Blandford, & Rees (1980), who also noted that double-peaked emission lines could be an observational consequence of such a scenario. Gaskell (1983, 1988, 1996a, 1996b) identified a number of radio-loud AGNs with displaced broad emission lines as candidate supermassive binaries and proposed that supermassive binaries are very common in both radio-loud and radio-quiet AGNs, with double-peaked emitters being the most obvious cases. In this scenario the spectroscopic properties of the double-peaked emitters should not differ from those of the average
(radio-loud) AGN, which is in contradiction with the observational properties described in §§ 5 and 6.2 (most notably with the dramatic difference between the profiles of the Hα and Lyα lines of Arp 102B and the reverberation of the Hα line of 3C 390.3).

Another serious disagreement between this scenario and the observations results from its prediction that the two peaks of a double-peaked line should drift in opposite directions as a result of the orbital motion of the binary. Although the expected orbital periods can range from decades to centuries, the signature of orbital motion can be detected in spectra spanning one or two decades. Thus, Halpern & Filippenko (1988, 1992) searched for radial velocity variations in the displaced peaks of Arp 102B and 3C 332, using spectra spanning a decade, but did not find any. A more extensive study of Arp 102B, 3C 390.3, and 3C 332 by Eracleous et al. (1997) did not find any evidence for orbital motion; a suggestive variability trend found by Gaskell (1996a) in 3C 390.3 lasted only until 1988 (Eracleous et al. 1997; Shapovalova et al. 2001; Sergeev et al. 2002). The lack of evidence for orbital motion yielded lower limits on the binary masses of $10^{10}$–$10^{11} M_\odot$, which are in conflict with a number of other observations and with theory, leading to the rejection of this scenario as a general explanation for double-peaked emission lines (see Eracleous et al. 1997 for a more detailed discussion).

6.4.2. Emission from a Bipolar Outflow

Since double-peaked emitters are radio-loud AGNs, it is conceivable that the double-peaked lines arise in a bipolar outflow resulting from the interaction of the powerful radio jets with gas immediately around the central engine. Norman & Miley (1984) discussed the interaction of the jets with the emission-line regions in qualitative terms, while Zheng, Binette, & Sulentic (1990) constructed quantitative models for the profiles of emission lines produced in the outflow. Such models were applied to the double-peaked Hα lines of 3C 390.3 and Pictor A by Zheng, Veilleux, & Grandi (1991) and Sulentic et al. (1995b), respectively. Bipolar outflow models are not immediately appealing, however, because statistical studies of the Hβ profiles of radio-loud AGNs suggest that the line-emitting gas is arranged in a flat disk perpendicular to the radio axis (see, for example, Wills & Browne 1986; Jackson & Browne 1991b; Brotherton 1996; Marziani et al. 1996). The conclusions of these studies and the fact that most double-peaked emitters are associated with double-lobed radio sources argue against bipolar outflows and contradict the suggestion by Sulentic et al. (1995b) that double-peaked emitters represent an extreme segment of the radio-loud AGN population in which the axis of the outflow is oriented very close to the line of sight. The following additional observational constraints make bipolar outflow models for double-peaked emission lines unlikely:

1. The dramatic difference between the observed Lyα and Hα profiles of Arp 102B (Halpern et al. 1996) cannot be easily explained. The radial velocity gradient in the outflow should reduce the optical depth of Lyα photons and allow them to escape easily with the consequence that Lyα and the Balmer lines should have similar profiles.

2. Reverberation mapping of 3C 390.3 (see § 6.2) has shown that both sides of the Hα line respond together to changes in the ionizing continuum, contrary to the expectation that the blueshifted side of the line should respond first, with hardly any lag from the continuum variations.

3. If the double-peaked lines of 3C 390.3 originate in a bipolar outflow, the reverberation results reviewed in § 6.2 imply that the outflow should be viewed nearly at right angles to its axis ($i > 84°$, following Livio & Pringle 1996 and Livio & Xu 1997). However, this orientation is in contradiction with the observed radio properties of 3C 390.3 (see discussion in § 6.2).

6.4.3. Spherically Symmetric Broad-Line Region, Illuminated Anisotropically

This model was discussed in its general form by Goad & Wanders (1996) although it was originally considered by Wanders et al. (1995) as an interpretation of the reverberation mapping results for the Seyfert galaxy NGC 5548. The broad-line region is assumed to consist of a large number of clouds in randomly inclined Keplerian orbits occupying a thick spherical shell. The clouds are photoionized by a central source (presumably an accretion disk) that emits anisotropically. In the specific picture discussed by Goad & Wanders (1996) the anisotropic emission was described by two conical beams that could possibly be superposed on an isotropic “background” illumination. For specific combinations of the beam opening angle and orientation of the observer relative to the axis of the beam, the resulting emission-line profiles appear double peaked and the expected frequency of double-peaked lines is consistent with what is observed. It was also suggested that the UV spectrum of Arp 102B could be explained in this context if the ionizing continuum consists of a hard X-ray power law emitted isotropically and a softer, UV bump spectrum making up the two conical beams (inspired by Netzer 1987). Moreover, high- and low-ionization lines would, in general, have different profiles. Thus, an observer whose line of sight is within the cone of the UV beam would find the Lyα and C iv lines to be relatively narrow and single peaked, but the Balmer and Mg ii lines would appear very broad and double peaked, just as observed in Arp 102B. The weakness of the nonstellar continuum in the optical spectra of double-peaked emitters could also be explained by placing the observer’s line of sight outside of the cones of the UV beams.

Although this scenario has its attractions, its applicability to double-peaked emitters does not withstand close scrutiny. It is at odds with the observations in the following ways:

1. It does not provide a self-consistent explanation of all of the properties of Arp 102B: in order to explain the difference between the profiles of the Lyα and Balmer, the observer’s viewing direction must lie within the conical UV beams, but to explain the weakness of the nonstellar continuum relative to the starlight, the observer’s viewing direction must be outside the conical UV beams.

2. It does not explain the unusually strong low-ionization narrow lines of double-peaked emitters.

From a theoretical perspective the physical basis for the assumed cloud distribution and kinematics is questionable. Even if such a system of clouds on randomly inclined, Keplerian orbits could be produced at all, it would be destroyed by collisions in 100 dynamical times, or in 200 yr in the case of 3C 390.3 (see the general estimate and
6.5. Connection of Double-peaked Emitters with the Greater AGN Population

If the Hα emission line profiles of approximately 20% of radio-loud AGNs are to be attributed to accretion disks, what of the remaining objects? Our understanding of the dynamics of the line-emitting gas would improve tremendously if a single model could be found that would describe the majority of emission-line profiles, especially if the same model can explain double-peaked profiles. As such, double-peaked emission lines place important constraints on any model that seeks to explain AGN broad-line regions in a universal way.

A possible new clue is the discovery of double-peaked Balmer emission lines in many LINERs, which underscores the connection between the two types of hosts. Examples of LINERs with double-peaked emission lines include NGC 1097 (Storchi-Bergmann, Baldwin, & Wilson 1993), M81 (Bower et al. 1996), NGC 4203 (Shields et al. 2000), NGC 4450 (Ho et al. 2000), and NGC 4579 (Barth et al. 2001). The prototypical double-peaked emitter, Arp 102B, is also a LINER (Stauffer, Schil, & Keel 1983). Since LINERs are found in about 30% of all nearby galaxies and a significant fraction of them could be AGNs, the incidence of double-peaked emission lines among the entire AGN population could be quite high. The exact fraction of AGNs among LINERs and the frequency of double-peaked emission lines in LINERs remain to be quantified, however.

Motivated by these considerations, we explore here whether accretion disk models, which offer the best explanation for double-peaked lines, can also explain the single-peaked profiles observed in the majority of AGNs. In support of this approach, we note that our comparison of the widths and shifts of double-peaked and single-peaked emission lines suggests a similarity between the corresponding broad-line regions. Furthermore, if we attribute the mean redshift measured over all radio-loud AGNs to the combined effects of gravity and transverse motions of the line-emitting gas in a Keplerian disk, it allows us to infer a characteristic distance of the line production site from the central object of 6000 r_p, comparable to the outer radii of the line-emitting disks found in § 4 and in Paper I. This estimate supports the above suggestion that all radio-loud AGNs may harbor line-emitting accretion disks and/or additional line-emitting gas in related structures (e.g., an accretion disk wind).

The following possibilities for the origin of single-peaked lines in accretion disks have been discussed in the literature:

1. The line-emitting disk in most AGNs could be quite large with a ratio of outer to inner radius of order 10 or more. This would bring the two peaks of a double-peaked line close together and make the profiles appear single peaked (Dumont & Collin-Souffrin 1990a; Jackson, Penston, & Pérez 1991). To illustrate this point, we have simulated Hα spectra by assuming that the broad Hα line is produced in a large accretion disk, namely, one with an inner radius of order a few hundred r_p and an outer radius greater than 10^4 r_p, i.e., ξ_2/ξ_1 ~ 10–100. To complete the simulation, we added the usual narrow lines in the vicinity of Hα and Poisson noise. The narrow lines were assumed to have Gaussian profiles with a FWHM of a few hundred kilometers per second, while the noise was generated assuming a S/N of 30–200 in the continuum. We explored a range of inclination angles between 10° and 40° and a range of emissivity power-law indices between 1.5 and 3. In Figure 9 we show a montage of simulated spectra spanning a range of parameter values. These examples were chosen because they resemble very closely some of the observed Hα spectra presented in Paper I. Thus, large accretion disk models can reproduce, at least qualitatively, a wide variety of profiles observed in radio-loud AGNs. Moreover, red asymmetries are quite common, particularly below half-

2. The disks in most AGNs could be oriented close to face-on. This possibility was explored by Corbin (1997a), who computed the profiles resulting from nearly face-on, flattened broad-line regions resembling face-on disks. Some of the simulated Hα profiles that we present in Figure 9 also correspond to face-on disks. The main conclusion from these calculations is that face-on disk models reproduce many of the desired properties of observed line profiles, including a single peak, extended red wings (i.e., redward asymmetries), and a net redshift of the entire line.

3. Double-peaked line profiles from a disk can easily be turned into single-peaked profiles by the presence of a disk wind. Murray & Chiang (1997) have shown that although the outflow velocity of the wind is much smaller than the rotational velocity, its velocity gradient is as large as the rotational velocity gradient. The main physical consequence is that photons can escape much more easily along lines of sight with a small projected velocity. The resulting line profiles are single peaked with broad wings even though the emission comes from gas that is essentially on circular orbits. This was illustrated clearly by Murray & Chiang (1997), who computed profiles of UV resonance lines arising in a wind and compared them to observed line profiles of quasars. An additional illustration was provided by Chiang & Murray (1996), who showed that the observations of reverberation in the C IV line of NGC 5548 could also be explained, at least qualitatively, in the context of an accretion disk wind model.

Of the possibilities discussed above, we favor the accretion disk wind scenario because of a number of additional appealing features that it possesses, as we discuss further below. In particular, it offers a way of connecting double-peaked emitters to the greater AGN population. It also provides an explanation for the Hα blueshifts observed in some double-peaked emitters (see Fig. 3 and § 3), since a
low optical depth wind can impart a blueshift on lines from
disk without altering their double-peaked profiles. We
therefore propose that the wind is the broad-line region in
most AGNs, which accrete at rates that are a sizeable frac-
tion of the Eddington rate. This idea is by no means new; it
was suggested, for example, by Murray et al. (1995) to
explain broad absorption line quasars and by Elvis (2000) to
explain the absorption features observed in the X-ray spec-
tra of quasars. The dynamics of the wind were worked out
analytically by Murray et al. (1995) and through detailed
numerical simulations by Proga, Stone, & Drew (1999) and
Proga, Stone, & Kallman (2000), which confirm the general
analytic results.

To show how double-peaked emitters and low-luminosity
AGNs fit into this scheme, we note that the structure of the
accretion flow is controlled largely by the Eddington ratio,
i.e., the ratio of the accretion rate to the Eddington rate
($\dot{M}/M_{\text{Edd}}$). At large Eddington ratios ($\dot{M}/M_{\text{Edd}} \gtrsim 0.1$) the
inner accretion disk is geometrically thin and optically
thick, as described by the model of Shakura & Sunyaev
(1973). Its emitted SED has a prominent UV bump, which
exert a substantial radiation pressure on the atmosphere
of the outer disk via resonance-line absorption, accelerat-
ing a wind. We posit that such a structure applies to Seyfert
galaxies and quasars. At the opposite extreme of a low
Eddington ratio ($\dot{M}/M_{\text{Edd}} \lesssim 10^{-2}$) the inner disk changes to
an ion torus whose emitted SED is a hard X-ray power law
without a UV bump. When such a hard spectrum impinges
on the atmosphere of the outer disk, it ionizes it and reduces
the potential of exerting radiation pressure via resonance-
line absorption (see, for example, the discussion by Murray
et al. 1995). The potential for a significant radiation pressure
is reduced further by the lack of substantial numbers of UV
photons in the incident SED. Thus, the wind becomes feeble
and the accretion disk is unveiled, allowing the observer to
see double-peaked emission lines from the disk proper. In
such objects the feeble wind would be the primary source of
UV resonance emission lines, which would be single peaked
as a result of their origin (see the discussion by Collin-
Souffrin & Dumont 1989). Moreover, the wind may also be
observable through absorption lines that it produces. Such
windlike absorption lines have actually been detected in
Arp 102B (Halpern et al. 1996; Eracleous, Halpern, &
Charlton 2003) and other double-peaked emitters
(Eracleous 2002).

7. EPILOGUE

We have presented the completion of our survey of
moderate-redshift, radio-loud AGNs whose primary moti-
vation was to search for more examples of double-peaked
emission lines. We find that 20% of the objects surveyed
have H$_\alpha$ lines with double peaks or twin shoulders. In 17 of
the 24 cases the blue peak/shoulder is stronger than the red.

Fig. 9.—Simulated spectra of the H$_\alpha$ region. Disk models with parameters as indicated are used for the broad H$_\alpha$ profiles, while the profiles of the narrow lines are described by Gaussians of FWHM of a few hundred kilometers per second. To make the spectra look as realistic as possible, Poisson noise has also been added, assuming $S/N \approx 30\text{--}200$ in the continuum. The model parameters were tuned so that these simulated spectra resemble the observed spectra of objects from Paper I (as labeled in the figure).
The H\textalpha\, profiles of 13 of these 17 objects can be fitted quite well by the simplest possible disk model (homogeneous and axisymmetric). The H\textalpha\, profiles of many of the remaining objects can be fitted by more sophisticated disk models (nonaxisymmetric and/or inhomogeneous). Double-peaked emitters possess a number of additional properties that distinguish them from the average radio-loud AGN and make them similar to accretion-powered LINERs. A consideration of all of the available data shows an origin of double-peaked emission lines in an accretion disk to be the preferred interpretation. Alternative scenarios are rather unsatisfying: although they can produce double-peaked emission lines, at least in principle, they cannot explain all of the properties of double-peaked emitters, they fail some direct observational tests, and in some cases their physical foundations do not withstand close scrutiny.

A physical model in which the inner accretion disk is an ion torus that illuminates the outer disk can explain the observed properties of double-peaked emitters. This model also provides a framework in which the connection between double-peaked emitters and the greater AGN population can be sought. More specifically, we propose that in most AGNs the broad-line region is an accretion disk wind, while in double-peaked emitters and other low-luminosity AGNs (such as some LINERs) the broad-line region is the outer accretion disk. This transformation is brought about by a decline of the accretion rate from a sizable fraction of the Eddington rate to values that are more than 2 orders of magnitude lower. At these extremely low accretion rates the structure of the inner disk changes to an ion torus and the wind that cloaks the outer disk diminishes. This scenario can be tested by comparing the profiles of UV resonance lines with the profiles of the Balmer lines of double-peaked emitters.

Even though our survey targeted radio-loud AGNs so as to maximize the efficiency of finding double-peaked emitters, radio-quiet AGNs also host double-peaked emission lines. As we noted in § 6.5, a significant number of LINERs have recently been found to possess double-peaked Balmer lines. LINERs have been traditionally regarded as radio-quiet objects, but it was recently argued by Ho et al. (2000) and Terashima & Wilson (2003) that the ratio of the radio luminosity of LINERs to their nonstellar optical luminosity is considerably higher than that of radio-quiet AGNs. The much larger sample of 116 double-peaked emitters found in the Sloan Digital Sky Survey (SDSS; see Strateva et al. 2003) comprises 76% radio-quiet AGNs, indicating that radio-quiet double-peaked emitters are more numerous than radio-loud ones. However, double-peaked emitters are 1.6 times more likely to be found among radio-loud AGNs.

Finally, although it is beyond the scope of this paper, variability of double-peaked profiles deserves discussion. We distinguish two types of variability: (1) short-term variability of the line flux due to reverberation of the ionizing continuum (timescales of order weeks), and (2) long-term variability of the line profiles (timescales of order months to years). In this paper we have made extensive use of the results of reverberation mapping of 3C 390.3 (Dietrich et al. 1998; O’Brien et al. 1998; Sergeev et al. 2002) because their implications are straightforward and important. Since such experiments have been performed only for 3C 390.3, we have taken these results to be representative of all double-peaked emitters. However, reverberation mapping of additional objects is sorely needed to check their behavior and to measure the dimensions of the line-emitting region.

Studies of long-term profile variations of the line profiles have been carried out for a handful of double-peaked emitters, namely, 3C 390.3 (e.g., Zheng et al. 1991; Eracleous et al. 1997; Gilbert et al. 1999; Sergeev et al. 2002), Arp 102B (e.g., Miller & Peterson 1990; Newman et al. 1997), NGC 1097 (Storchi-Bergmann et al. 1995, 1997, 2003), and 3C 332 (Eracleous et al. 1997; Gilbert et al. 1999), and profile variability results on Pictor A have also been reported (Halpern & Eracleous 1994; Sulentic et al. 1995b; Eracleous & Halpern 1998), but no comprehensive study exists yet. The long-term variability patterns show a wide variety, although the most pronounced and obvious pattern is the slow and systematic modulation of the relative strengths of the two peaks. In this paper we have appealed to profile variations primarily to test the binary black hole hypothesis. However, the interpretation of the long-term profile variations is not yet clear, and they do not yet constitute a straightforward test of scenarios for the origin of the lines. Such slow variations are certainly not the result of reverberation of a variable ionizing continuum since the light crossing time of the line-emitting region is of order a few weeks (see § 6.2). More generally, reverberation mapping of Seyfert galaxies has shown that although the integrated fluxes of broad emission lines do vary in response to a variable ionizing continuum, the line profiles do not (e.g., Ulrich et al. 1991; Wanders & Peterson 1996; Kassebaum et al. 1997). The timescales on which the line profiles change significantly are longer than the dynamical time of the line-emitting region by a factor of several. Now that accretion disk emission is emerging as the favorite scenario for the origin of double-peaked emission lines, we will be able to investigate the origin of the observed profile variations through detailed case studies and exploit them to learn about dynamical phenomena in AGN accretion disks.

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