An X-ray Luminous, Dwarf Seyfert Companion of Mrk 273

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ABSTRACT

We report the discovery of the brightest X-ray source hosted by a faint ($M_B = -16$) dwarf galaxy in the immediate vicinity of the ultraluminous IRAS merging galaxy Mrk 273. The dwarf galaxy, $1.3'$ away from Mrk 273, is at the tip of a faint northeast plume of Mrk 273. Its spectrum exhibits strong [OIII], Hα, [NII] emission lines, which establish the redshift of the dwarf galaxy, $z = 0.0376$, the same as that of Mrk 273. The emission line ratios are typical of Seyfert galaxies. The X-ray emission is consistent with a point-like source coincident with the center of the dwarf galaxy. The intrinsic X-ray luminosity, 6.3×10^{41} ergs s^{-1}, in the 0.1–2.4 keV energy range, is about seven times larger than the B band luminosity. The X-ray spectrum of the source can be fit with a power-law. All the evidence is consistent with the source being a Seyfert galaxy. Out of $\sim$ 10 faint objects in the same field only one is detected by ROSAT and its ratio of soft X-ray to optical luminosity is as high as those for BL Lac objects and few active galactic nuclei (AGNs). If there is a population of such dwarf AGNs hidden as companions of major merger galaxies (such as Mrk 273), they may contribute to the luminosity function of AGNs and the cosmic X-ray background at the faint end.

Subject headings: galaxies: active – galaxies: individual (Mrk 273) – galaxies: nuclei – galaxies: Seyfert – X-ray: galaxies

1. Introduction

During the cross-correlation of ultraluminous IRAS galaxies (ULIRGs) selected from 1.2Jy (Fisher et al. 1995) and QDOT all sky redshift survey (Lawrence et al. 1998) with X-ray sources from ROSAT All Sky Survey and archive data, we found that some ULIRGs have soft X-ray companions within a few arcminutes of each source. The optical counterparts of these companions are much fainter than the primary target objects (Xia et al. 1998). This phenomenon was first mentioned by Turner, Urry & Mushotzky (1993) using ROSAT PSPC observations of six Seyfert 2 galaxies. However it was unclear whether the soft X-ray companions are physically associated with the target galaxies or they were just the result of chance alignment (see below). The origin of the soft X-ray emission from these companions is not well understood: presumably it is closely related to the interacting and/or merging process that is occurring in almost all ULIRGs (e.g., Sanders & Mirabel 1996; Wu et al. 1998 and references therein).

To understand the physical connection between the soft X-ray companions with the primary targets, we initiated an optical spectroscopic program to observe the faint counterparts of soft X-ray companions in Arp 220, Mrk 231 and Mrk 273. For Arp 220 ($z = 0.018$), the counterpart of the soft X-ray companion is likely a background group or cluster with redshift of about 0.1. For Mrk 231 ($z = 0.042$), the counterparts are very likely background QSOs with redshift larger than 1. However, for Mrk 273 ($z = 0.0378$), our observations show that its soft X-ray companion is physically associated with Mrk 273 because the faint counterpart at the center of soft X-ray emission has the same redshift as Mrk 273. The counterpart, which we term as Mrk 273x, turns out to be a nucleated dwarf galaxy. The few dwarf galaxies detected previously in X-ray have X-ray luminosities $\lesssim 10^{39}$ ergs s^{-1} (e.g., Gizis, Mould & Djorgovski 1993 for Fornax; Papaderos et al. 1994 for BCD VII ZW 403; Martin & Kennicutt 1995 for NGC 5253; Hensler et al. 1996 for NGC

1705). The search for low-luminosity Seyfert nuclei in nearby galaxies by Ho, Filippenko, & Sargent (1997) did not find any Seyfert nucleus for sources fainter than $M_B \approx -17.5$. The optical counterparts for broad line AGNs selected from Einstein Observatory Extended Medium Sensitivity Survey are generally brighter than $M_B = -18$ (Della Ceca et al. 1996). In contrast, the soft X-ray luminosity of Mrk 273x is 6.3×10^{41} ergs s^{-1}, more than two orders of magnitude higher than those from other dwarf galaxies, and is by far the brightest observed to date. In §2 and 3, we report the optical and X-ray observations of Mrk 273x. Combined with the recent VLA 21cm continuum and HST WFPC2 archive observations, we demonstrate that this object is a unique dwarf AGN. We discuss the implications of Mrk 273x in §4. Throughout this paper, we use a Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1}.

2. Observations and Data Reduction

The observations with the Position Sensitive Proportional Counter (PSPC) and High Resolution Imager (HRI) instruments on board the ROSAT X-ray satellite for the Mrk 273 field were carried out during May and June 1992 as archived. The total exposure times are 37.6ksec and 19.3ksec for the PSPC and HRI respectively. Fig. 1 (plate) shows the soft X-ray contours from the ROSAT HRI image overlaid on the optical image scanned from an R film of the second Palomar Observatory Sky Survey (POSS II). One can see a strong soft X-ray companion $1.3'$ (84 kpc in projected distance) to the northeast of Mrk 273. At the center of the soft X-ray companion, a faint optical counterpart is clearly visible. This counterpart (which we call Mrk 273x), is at the tip of the northeast plume of Mrk 273. The apparent B and R magnitudes for Mrk 273x are about 20.8 and 19.6, respectively, from the USNO-A1.0 catalog (Monet 1996). In order to know if the soft X-ray companion is physically associated with Mrk 273, we observed this object on 12 April, 1997 using a Zeiss universal spectrograph mounted on the 2.16m telescope at Xinglong Station of

Beijing Astronomical Observatory (BAO). A Tektronix 1024×1024 CCD was used giving a wavelength coverage of 3500Å to 8100Å with a grating of 195Å/mm and a spectral resolution of 9.3Å (2 pixels). Wavelength calibration was carried out using an Fe-He-Ar lamp; the resulting wavelength accuracy is better than 1Å. KPNO standard stars were observed to perform flux calibrations.

The optical spectral data reduction was performed using IRAF packages at BAO. The CCD data reduction includes standard procedures such as bias subtraction, flat fielding and cosmic ray removal. All the X-ray data reduction was carried out at the Max-Planck-Institut für Extraterrestrische Physik using the EXSAS software. The detected photon counts from the companion of Mrk 273 by PSPC and HRI are 444 and 61, respectively. The HRI data can be used to determine the image position with an accuracy $\leq 5''$. The PSPC data, on the other hand, allow one to do a spectral analysis in the 0.1–2.4 keV energy band, obtain the radially averaged intensity profiles (deconvolved with the PSPC point-spread function) and test time variability.

3. Results and Analysis

3.1. The Optical Spectroscopy of Mrk 273x

The optical spectrum for Mrk 273x is shown in Fig. 2. The measurement of line emissions was performed using IRAF tasks "splot" and "ngaussfit". Since Hα emission is heavily blended with [NII]λ6584, a double-Gaussian fit was employed. The inset in Fig. 2 shows that the fit is quite satisfactory. The redshift of Mrk 273x determined from the Hα emission line is $z = 0.0376$, nearly identical to that of Mrk 273. From the apparent magnitudes, $B = 20.8$ and $R = 19.6$, we obtain absolute magnitudes -16 and -17.2 for the B and R band, respectively. Since there is no significant dust extinction for Mrk 273x (see

discussion, §4), the inferred low optical luminosity implies that Mrk 273x is a dwarf galaxy.

The measured line flux, equivalent width (EW) and full width at half maximum (FWHM) for all identifiable emission lines are listed in Table 1. As we can see from Table 1 and Fig. 2, the high excitation emission lines [OIII]λ4959,5007 are very strong and the ratio of the [OIII] lines to Hβ is as large as 10. We have also calculated the line ratios, such as [OIII]λ5007/Hβ, [NII]λ6584/Hα, [SII]λ6716+6731/Hα, and [OI]λ6300/Hα, and put the results on the diagnostic diagrams of Veilleux & Osterbrock (1987). The positions of these line ratios on the diagrams leave little doubt that Mrk 273x is a Seyfert galaxy. The FWHM of the Hα emission is 15.3Å, which corresponds to about 700 km s^{-1}. The FWHMs of other permitted and forbidden lines are similar (cf. Table 1). These (narrow) widths of the emission lines classify Mrk 273x as a type 2 Seyfert galaxy (Osterbrock 1989).

3.2. The Soft X-ray Properties of Mrk 273x

We fit the soft X-ray spectrum with single power-law, thermal bremsstrahlung, black body, and Raymond-Smith thermal plasma models. Although all these models are acceptable from the point of view of χ^2, the inferred values for the absorbing gas column density, $N_{\rm H}$, for the last 2 models are unreasonably low – even lower than the known Galactic contribution. The best power-law fit has $N_{\rm H} = (4.3 \pm 2.2) \times 10^{20}{\rm cm}^{-2}$, and a photon index of -1.98, a typical value for broad-line Seyfert galaxies. Using this index, the model dependent soft X-ray flux in the 0.1–2.4 keV band is $f_X = 1.1 \times 10^{-13}$erg cm^{-2} s^{-1}. The corresponding soft X-ray luminosity for Mrk 273x is 6.3×10^{41} ergs s^{-1}, again in the range of Seyfert galaxies. The intrinsic X-ray luminosity obtained with a thermal bremsstrahlung fit ($kT \approx 1.6$keV) is smaller by $\approx 5\%$. For comparison, the B magnitude for Mrk 273 is $B = 15.7$ and its soft X-ray flux is $f_X = 1.25 \times 10^{-13}$erg cm^{-2} s^{-1}. Therefore, Mrk 273x is as bright as Mrk 273 in the soft X-ray band, despite the fact that it is one hundred times

less luminous than Mrk 273 in the optical as well as in the 21cm radio continuum (cf. Fig. 1).

The HRI image (shown as contours in Fig. 1) has a pixel scalelength of $1.0''$ and the effective resolution (FWHM) of the Gaussian filtered image is about $5''$. The coordinates of Mrk 273x in the HRI image agree with those determined from the POSS II plate within the HRI position accuracy. We have also performed spatial analysis for the PSPC and HRI data. The resulting radial distributions are consistent with the companion being a point source. Since the X-ray observations were carried out in multiple-epochs, we performed χ^2 tests to see whether the observed counts differs from a constant average emission for Mrk 273 and its companion. No significant variability was found for either source during May and June of 1992.

3.3. Multi-Wavelength Comparisons of Mrk 273x

Recently Yun & Hibbard (1998) obtained a radio continuum map for the Mrk 273 system using VLA. Extraordinarily extended radio lobes from Mrk 273 of ~ 200 kpc in length are detected. Mrk 273x has been clearly detected as well with a flux $f_\nu = 1.45$mJy at (observed frequency) $\nu = 1.37$GHz. Mrk 273x was unresolved due to the large synthesized beam, $19''.6 \times 18''.4$, but it is consistent with being a compact point-like radio source. Hibbard & Yun (1998) have also mapped HI in this system. A tidal HI tail was observed in the southern luminous tail, but not in the much fainter northeast tail nor from Mrk 273x. Unless this dwarf AGN is very HI gas-rich, the non-detection of HI is expected, given the small source size and large distance; it is also in agreement with the small $N_{\rm H}$ value inferred from the X-ray analysis (see §3.2).

These multi-wavelength observations show that Mrk 273x has an unusual

spectral energy distribution. The fluxes in the soft X-ray, optical and radio are $(1.1, 0.15, 2\times10^{-4})\times10^{-13}$ergs cm^{-2} s^{-1}, respectively, where we have estimated the radio flux using νf_ν at $\nu = 1.37$GHz. The flux ratios are therefore $f_X : f_B : f_{\rm radio} = 7 : 1 : 1.3 \times 10^{-3}$. Comparing with the sample of Griffiths et al. (1996) from five deep ROSAT fields show that such peculiar spectral energy distributions are very rare for AGNs. In particular, the $\log(f_X/f_B)$ for Mrk 273x is 0.86, which is only achieved by some BL Lac objects (Stocke et al. 1991), and few AGNs (Maccacaro et al. 1988). For comparison, the corresponding value for Mrk 273, also a Seyfert 2, is -1.18 (its value is probably lowered by the star formation induced in the merging process). To summarize, the radio, optical and X-ray observations all point to the existence of an AGN at the center of Mrk 273x.

4. Discussion

We have shown that Mrk 273x is a powerful soft X-ray source hosted by a faint dwarf galaxy. In fact, the soft X-ray luminosity for Mrk 273x is the brightest observed to date for a dwarf galaxy, more than two orders of magnitude brighter than those for other nearby dwarf galaxies (see introduction, §1).

As discussed in §2, Mrk 273x is a faint dwarf galaxy, with $M_B = -16$ and $M_R = -17.2$. So far, we have neglected the effect of dust extinction. We now proceed to remedy this. Following Gebel (1968) and Veilleux & Osterbrock (1987), the extinction in the B band is given by $A_B = 4 \times E(B-V) = 3.08 \times E_{\beta-\alpha}$, where $E_{\beta-\alpha} = 2.5\log[3.10/({\rm H}\alpha/{\rm H}\beta)]$, appropriate for AGNs (Miller & Mathews 1972). Using the Hα and Hβ fluxes listed in Table 1, we find that A_B is zero for Mrk 273x. The low extinction is in agreement with the low $N_{\rm H}$ value derived from the X-ray spectral analysis, and the non-detection of HI in the line emission at 21cm. The dwarf nature of Mrk 273x can be seen not only from its faint luminosity but also from its small size: its diameter is 7 kpc at most, about a factor

of 2 smaller than the upper limit, 12.8 kpc, for "true" dwarf galaxies classified by Pildis et al. (1997). The HST WFPC2 snapshot observations show a bright nucleus at the center of Mrk 273x; Mrk 273x is therefore one of the so-called nucleated dwarf galaxies (Ferguson & Binggelli 1994). On the other hand, Mrk 273x is also clearly a Seyfert galaxy. The overall optical spectrum, in particular the emission line ratios, of Mrk 273x is typical of Seyfert galaxies. The soft X-ray properties are characteristic of Seyfert 2 galaxies. The radio emission is consistent with a point-source, providing further support for the Seyfert nature of Mrk 273x. It is, however, unclear why Mrk 273x is the only X-ray luminous dwarf galaxy detected by ROSAT out of ~ 10 optically faint objects within $2'$ of Mrk 273 (cf. Fig. 1). A closer examination of the POSS II film (cf. Fig. 1) and HST images reveals that Mrk 273x is at the tip of the faint northeast plume from Mrk 273. It is possible that the high soft X-ray luminosity of Mrk 273x is somehow connected to these features.

The physical mechanism that produces the unusually high soft X-ray luminosity in Mrk 273x is unclear. Accretion onto a central black hole provides a plausible explanation (e.g., Lin, Pringle, & Rees 1988), although some contribution from starbursts is also possible (e.g., Terlevich et al. 1992). The X-ray luminosity could also have been boosted by relativistic effects such as a superluminal jet pointing toward us. Recent numerical simulations show that major mergers or "galaxy harassment" are very efficient transporting the gas to the centers of interacting galaxies (Mihos & Hernquist 1996; Lake, Katz & Moore 1998). It is much less clear whether the transported gas forms stars and/or is accreted onto a (pre-existing) black hole or even forms a black hole. If the transported gas is accreted onto a pre-existing black hole, then the mass of the black hole is $M_{\rm BH} \sim 5 \times 10^4 (0.1/\beta) M_\odot$, where β is the X-ray luminosity in units of the Eddington luminosity. The required accretion rate is $\dot{M} = L_X/(\eta c^2) = 10^{-4}(0.1/\eta) M_\odot$ yr^{-1}, where η is the conversion efficiency of the accreted mass into the soft X-ray radiation. The estimates for the mass and accretion rate are uncertain; the black hole mass is reminiscent of M32 which has $M_B = -16.6$ and a

black hole mass of $2.3 \times 10^6 M_\odot$ (Bender, Kormendy & Dehnen 1996; see also Magorrian et al. 1997).

The mechanism that powers Mrk 273x is unlikely to operate on Mrk 273x alone: there is likely some population of X-ray luminous dwarf AGNs around merging galaxies. The optical identification of the ROSAT deep survey by Schmidt et al. (1997) found that out of fifty X-ray sources, four remain unidentified; they suggest that two of these could have an unusually large ratio of X-ray to optical flux. In light of the discovery of Mrk 273x, it may be fruitful to see whether these are also produced by dwarf galaxies. In practical terms, Mrk 273x highlights an exciting way to detect faint AGNs, and potential black holes at centers of faint galaxies, by studying the optical counterparts of soft X-ray companions of Seyfert 2 galaxies and major merging galaxies. If X-ray sources like Mrk 273x exist in large numbers, they can make a non-negligible contribution to the X-ray background and the AGN luminosity function, especially at the faint end.

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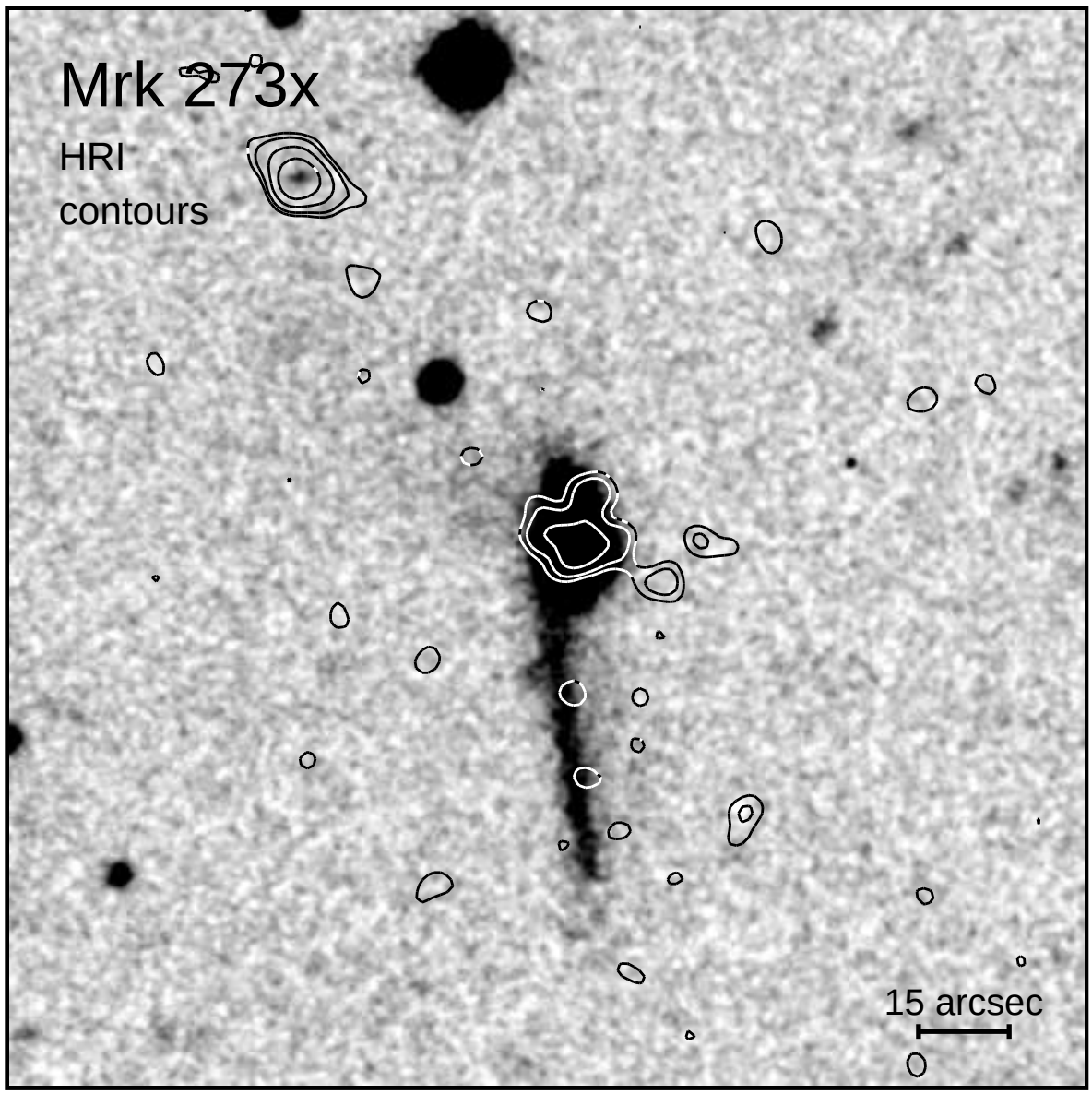

Fig. 1.— Overlay of the soft X-ray contours on the optical image centered on Mrk 273. The optical image is extracted from an R film POSS II catalog. The X-ray contours are computed from the ROSAT HRI image and are $3, 5, 10, 20\sigma$ of the background level, respectively. There is a bright soft X-ray companion, termed as Mrk 273x, $1.3'$ to the northeast of Mrk 273. Clearly there is a faint dwarf galaxy at the center of the X-ray emission of Mrk 273x. Approximately ten other faint objects are identifiable. There is also a (faint) northeast plume originating from Mrk 273. Mrk 273x is at the tip of the plume.

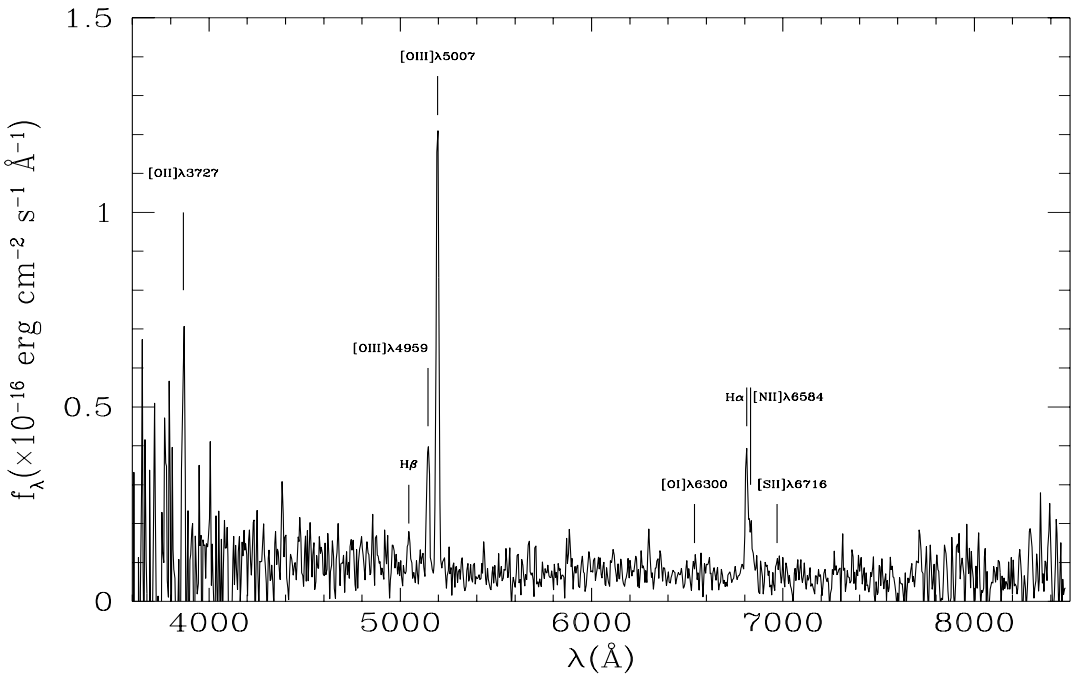

Fig. 2.— The optical spectrum of Mrk 273x. Some emission lines are indicated. The strong oxygen lines are characteristic of Seyfert galaxies. The inset shows a double-Gaussian fit to the Hα region. The dashed (dot-dashed) curve shows the Hα ([NII]λ6584) component, the dotted curve is their sum.

Table 1. Emission Line Properties for Mrk 273x

line	flux	error	EW	FWHM
[OII]λ3727	1.05e-15	20%	···	15.0
[OIII]λ4959	6.15e-16	10%	81.8	16.5
[OIII]λ5007	1.94e-15	10%	253.0	14.8
Hβ	1.90e-16	15%	27.5	18.0
[OI]λ6300	4.00e-17	100%	···	···
Hα	5.60e-16	20%	87.3	16.2
[NII]λ6584	2.50e-16	20%	39.1	16.2
[SII]λ6716	5.80e-17	$\geq$ 30%	···	···
[SII]λ6731	3.60e-17	$\geq$ 30%	···	···

Note. — The flux is in units of ergs cm^{-2} s^{-1} while the EW and FWHM are in units of Å. The EW of [OII] line is not given because the spectrum at $\sim$ 3700Å is too noisy to allow a reliable estimate of the continuum.