

Spatially Extended [P II] 1.188 μm and [Fe II] 1.257 μm Emission Lines in a Nearby Seyfert Galaxy NGC 1068 Observed with OAO/ISLE

Tetsuya HASHIMOTO,¹ Tohru NAGAO,^{2,3,4} Kenshi YANAGISAWA,⁵ Kenta MATSUOKA,² and Nobuo ARAKI²

¹*Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502*

tetsuya@kustro.kyoto-u.ac.jp

²*Graduate School of Science and Engineering, Ehime University, 2-5 Bunkyo-cho, Matsuyama, Ehime 790-8577*

³*Research Center for Space and Cosmic Evolution, Ehime University, 2-5 Bunkyo-cho, Matsuyama, Ehime 790-8577*

⁴*Optical and Infrared Astronomy Division, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588*

⁵*Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, Kamogata, Asaguchi, Okayama 719-0232*

(Received 2010 October 5; accepted 2010 November 29)

Abstract

We present *J*-band long-slit spectroscopic observation of NGC 1068 classified as a Seyfert 2 galaxy. *J*-band observations with OAO/ISLE provide clear detection of spatially extended [Fe II] 1.257 μm and [P II] 1.188 μm lines. We found that [Fe II] 1.257 μm /[P II] 1.188 μm increases with distance from a central continuum peak. Observed line ratios around the nucleus (continuum peak) are consistent with a typical value expected from photoionization models, while the ratios at 3''–4'' (210–280 pc) east and west of the nucleus are slightly higher than this. In the off nucleus region of NGC 1068 we also found a possible association between [Fe II] 1.257 μm /[P II] 1.188 μm and the radio continuum. This suggests a mild contribution of shock ionization induced by a radio jet outside nucleus while photoionization by the central energy source is dominant near the nucleus.

Key words: galaxies: individual (NGC 1068) — galaxies: nuclei — galaxies: Seyfert

1. Introduction

The narrow line regions (NLRs), which extend to several hundred or kilo parsec scale around the galaxy center, are the exclusive structure of active galactic nuclei (AGN) where the spatially resolved observations are possible. Therefore NLRs are often investigated as an important tool to study the ionization state of the interstellar medium (ISM) and/or chemical evolution in galactic scale (e.g., Nagao et al. 2006). Although it is widely accepted that the NLR is photoionized by ionizing photons radiated from a central engine, the possibility of shock ionization induced by a jet in off nucleus regions cannot be excluded since ionization photons decrease with distance from a nucleus (e.g., Fu & Stockton 2007). Thus, how much the shock contributes to the ionization of NLRs is very important to our understanding of AGN structure and in examining the utility of NLRs as a tool to investigate galactic-scale phenomena.

Furthermore, the shock ionization of NLRs is getting a lot more attention. Recent dramatic progress of theoretical simulations and observational studies of galaxy formation and evolution allow a quantitative comparison between both sides. In this context, a serious problem has arisen, i.e., theoretical simulations predict too many massive galaxies due to long-duration star formations in contrast to early-time quenching of star formation in observed massive galaxies (e.g., Croton et al. 2006; Bower et al. 2006). This problem cannot be solved even if a negative feedback effect on star formation activity caused by supernovae is involved and so AGN feedback effect is considered as a potential candidate of a solution: a massive galaxy likely has a supermassive black hole at its galaxy center, and inflow of ISM to a supermassive black hole invokes its

AGN activity which releases vast gravitational potential energy to ISM resulting in suppression of star formation activity (e.g., Scannapieco et al. 2005; Sijacki et al. 2007). However, how the AGN activity transmits its energy to ISM remains a mystery. One possible physical mechanism of the AGN feedback is shock ionization of ISM, i.e., the AGN activity inputs its energy to ISM through a shock heating induced by a jet.

In previous studies of NLRs, line-ratio diagnostics to distinguish between shock ionization and photoionization have been examined. Optical diagnostics, however, can hardly discriminate between the two mechanisms, because optical NLR spectra predicted by photoionization and shock ionization models are very similar to each other (Dopita & Sutherland 1995, 1996; Allen et al. 2008). The near infrared line ratio of [Fe II] 1.257 μm /[P II] 1.188 μm is one of the most powerful indicators to discriminate photoionization and shock ionization. Both lines have similar critical densities and excitation temperatures, i.e., this line ratio is roughly proportional to the ratio of gas-phase abundance of iron and phosphorous. In contrast, iron is a well known refractory species and is strongly depleted in dust grains, whereas phosphorous is a non-refractory species. Photoionization alone (including H II regions and NLRs excited by ionizing photons from young stars and AGN central sources, respectively) is relatively incapable of destroying the tough iron based grains, while these are easily sputtered by shocks. The [Fe II] 1.257 μm /[P II] 1.188 μm ratio, therefore, is high ($\gtrsim 20$) in fast shock-excited regions and low ($\lesssim 2$) in normal photoionized regions (Oliva et al. 2001). The actual ionization state of NLRs would be determined by the combination of photoionization and shock ionization, and so the observed line ratios are expected to change with the locations in NLRs ranging from

[Fe II] 1.257 μm /[P II] 1.188 μm ~ 2 to ~ 20 .

NGC 1068 is one of the nearest AGNs, which has a compact radio jet around the nucleus and spatially extended radio lobe (Wilson & Ulvestad 1983). This radio structure well coincides with a morphology of NLR (Capetti et al. 1997). Therefore, NGC 1068 is an ideal object with which to research the spatial distribution of [Fe II] 1.257 μm /[P II] 1.188 μm . In this paper, we adopt 14.4 Mpc as a distance to NGC 1068 and 1'' corresponds to 70 pc.

2. Theoretical [Fe II] 1.257 μm /[P II] 1.188 μm Ratio

Before describing the details of observation and data reduction, we summarize the theoretical background of [Fe II] 1.257 μm and [P II] 1.188 μm emission lines.

The emission line intensity is proportional to the product of the density of the ion responsible for the emission line process (n_i) and the electron density (n_e), multiplied by a function f giving the rate of the process. Thus the intensity ratio of two emission lines radiated from ions 1 and 2 is written as

$$\frac{I(\lambda_1)}{I(\lambda_2)} = \frac{n_{i,1}f_1}{n_{i,2}f_2}, \quad (1)$$

assuming the same spatial distribution of both ions (Osterbrock 1989). The function f involves the rate of emission line photons in the radiative transition from the excited level to the ground level written as

$$\frac{n_1 A_{10}}{n_0} = A_{10} \frac{q_{01}(T)}{q_{10}(T)} \left[1 + \frac{A_{10}}{n_e q_{10}(T)} \right]^{-1}. \quad (2)$$

Here A_{10} is the radiative transition probability, and q_{01} and q_{10} are collisional excitation and deexcitation rate, which include collisional strength (Ω). Thus, f can be calculated if A and Ω are known. Oliva et al. (2001) derived

$$\frac{n(\text{Fe})}{n(\text{P})} \lesssim \frac{n(\text{Fe}^+)}{n(\text{P}^+)} \sim 2 \cdot \frac{I([\text{Fe II}] 1.257 \mu\text{m})}{I([\text{P II}] 1.188 \mu\text{m})}, \quad (3)$$

using the collision strengths and transition probabilities of [Fe II] 1.257 μm and [P II] 1.188 μm (Krueger & Czyzak 1970; Zhang & Pradhan 1995; Mendoza & Zeippen 1982; Nussbaumer & Storey 1988). For solar abundance ratio of $n(\text{Fe})/n(\text{P}) \sim 100$ and typical depletion factor of Fe (~ 0.01) and P (~ 1.0 because of refractory species), equation (3) gives [Fe II] 1.257 μm /[P II] 1.188 μm close to unity, although the depletion factor of iron differs from object to object. Actually, [Fe II] 1.257 μm /[P II] 1.188 μm is $\lesssim 2$ in normal photoionized region, e.g., ~ 2 in Orion Bar (Walmsley et al. 2000). This is also true for NLR ionized by AGN radiation because even ionizing photons from AGN central source can hardly destroy the tough iron based grains in NLR.

However if shocks exist the grains are easily destroyed and gas-phase iron increases. As a result shock ionized gas represents high [Fe II] 1.257 μm /[P II] 1.188 μm ratio. If we assume that iron based grains are completely sputtered by shocks, the ratio becomes ~ 50 for solar abundance. This is similar to that measured in supernova remnants (e.g., $\gtrsim 20$ for LMC-N 63A and LMC-N 49 reported by Oliva et al. 2001).

The actual observed line ratio in NLR of AGN is expected to be between ~ 2 and ~ 20 since the ionization state would be

determined by the combination of photoionization and shock ionization if these exist as mentioned in section 1.

3. Observations and Data Reduction

Long-slit spectroscopy was carried out from 2009 November 8 to 12 with ISLE (Yanagisawa et al. 2006, 2008), which is a near-infrared imager and spectrograph for the Cassegrain focus of the 1.88 m telescope at Okayama Astrophysical Observatory (OAO). The camera used for the spectroscopic observations has a projected scale of 0''.25/pixel. The spectrum of NGC 1068 was obtained with a slit of 2''.0 (= 8 pixels) width and J -band grating which yields a 1.11–1.32 μm spectrum with a dispersion of 0.166 μm /pixel. The spectral resolution is ~ 1300 measured from an OH emission line at the central wavelength. The slit was oriented to E–W (i.e., position angle = 90°) and centered on the J -band continuum peak of NGC 1068 (figure 1). We note that the position angle is fixed to 90° in ISLE spectroscopic mode. Therefore, the slit was not placed along the major axis of NLR and the direction of the radio structure, at a position angle of $\sim 30^\circ$ (Das et al. 2006; Crenshaw et al. 2010). It lies outside of the nominal bicone of NLR and away from the axis of radio emission. Unfortunately other slit positions north and south of the nucleus could not be completed due to bad weather conditions. The acquisition consisted of a series of two 2-minute exposures with the object set at different positions along the slit followed by dome flats and calibration lamp of Argon and Xenon. The seeing size was 1''.0–2''.0. Since the weather conditions were not good throughout the observation, we excluded poor data from a total 6-hour exposure on source, resulting in the effective exposure time of 4.4 hours on source. The standard data reduction was performed for all selected spectra, i.e., dark frame subtraction, flat fielding,

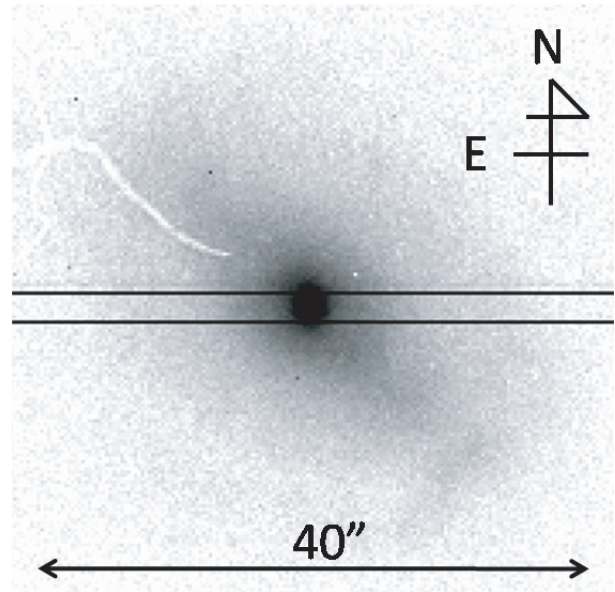


Fig. 1. J -band image of NGC 1068 obtained with OAO/ISLE in our observation. The long-slit position (P.A. = 90°) is shown by two solid lines.

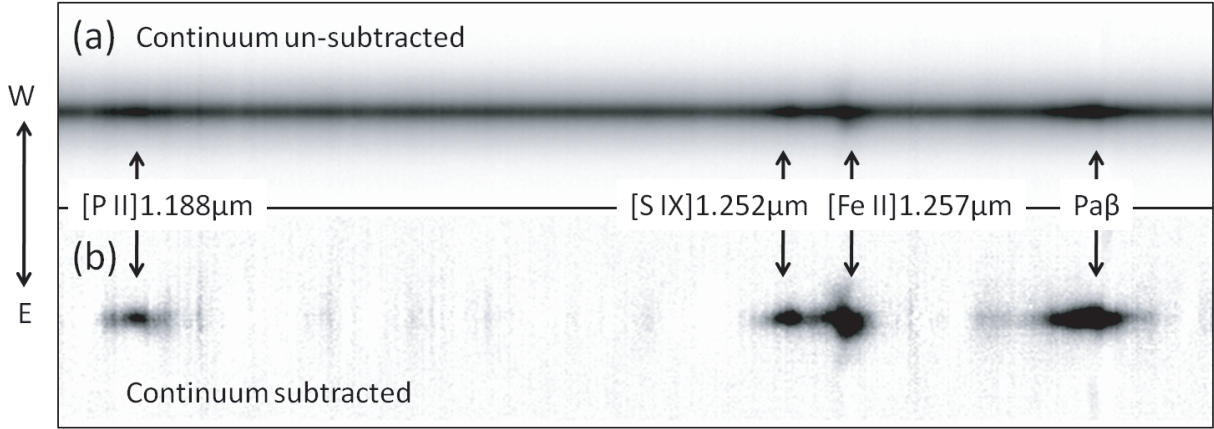


Fig. 2. 2-D spectra in J band extracted from central $\pm 15''$ region (a) and continuum-subtracted spectrum (b).

wavelength calibration, and sky subtraction using IRAF software. To correct the atmospheric spectral response and the instrumental efficiency, spectra of NGC 1068 were divided by spectra of some A-type rationing stars (HIP 5310, HIP 10795, HIP 14077, and HIP 22774) with the same airmass. In this reduction, the black body and $\text{Pa } \beta$ absorption features of rationing stars were removed by spectral fitting with a black body function and Voigt profile, respectively. The assumed effective temperatures of rationing stars are 8270, 7500, 8200, and 9230 K for HIP 5310 (A3 V), HIP 10795 (A7 V), HIP 14077 (A5 V), and HIP 22774 (A1 V), respectively.

4. Results and Discussion

The obtained 2-D spectra of NGC 1068 are displayed in figure 2. We detected [Fe II] 1.257 μ m and [P II] 1.188 μ m lines as well as $\text{Pa } \beta$ and [S IX] 1.252 μ m. The spatial extent of [Fe II] 1.257 μ m and [P II] 1.188 μ m are $\sim 14''$ and $\sim 7''$. These values are clearly larger than the typical seeing size of $1''.0$ – $2''.0$. Thus, we concluded that spatially extended [Fe II] 1.257 μ m and [P II] 1.188 μ m were successfully detected.

The line fluxes were measured from spectral fitting analysis with IRAF specfit task (Kriss 1994), assuming single Gaussian and underlying linear functions for each emission line. We summarized relative line fluxes normalized by [P II] 1.188 μ m in table 1, extracted from central $2''.0$ region and east and west neighbor regions. The detailed spatial distribution of [Fe II] 1.257 μ m/[P II] 1.188 μ m line ratios is shown in figure 3a.

Oliva et al. (2001) reported that the line ratio in the central $\sim 2''$ region of NGC 1068 is about 1.5. Since this value corresponds with the photoionization scheme as mentioned above, they concluded that in the central region most iron is locked into grains and shock excitation is not the primary origin of [Fe II] line emission. This explanation is relatively straightforward because there would be a large number of ionizing photons near the nucleus, that is enough to dominate the ionization of surrounding gases. Our measurement of [Fe II] 1.257 μ m/[P II] 1.188 μ m ~ 1.3 in the central $2''$ region is consistent with this value.

However, this argument may not be valid at off nucleus regions. We found that [Fe II] 1.257 μ m/[P II] 1.188 μ m

Table 1. Relative line fluxes normalized by [P II] 1.188 μ m.*

Line ID	East $3''.0$	Central $2''.0$	West $3''.0$
[P II] 1.188 μ m	1.0 ± 0.29	1.0 ± 0.02	1.0 ± 0.08
[S IX] 1.252 μ m	1.05 ± 0.02	1.01 ± 0.02	0.73 ± 0.07
[Fe II] 1.257 μ m	1.79 ± 0.02	1.33 ± 0.05	1.63 ± 0.07
$\text{Pa } \beta$	2.35 ± 0.04	2.89 ± 0.05	2.55 ± 0.08

* Spectra were extracted from central $2''.0$ region and east and west neighbor $3''.0$ regions.

increases with distance from a central continuum peak. While observed line ratios around the nucleus are consistent with a prediction by photoionization models, the ratios at $3''$ – $4''$ east and west of the nucleus (~ 560 pc) are slightly higher than the typical value of [Fe II] 1.257 μ m/[P II] 1.188 μ m in the photoionized region. Although there are only two research efforts devoted to the spatial distribution of [Fe II] 1.257 μ m/[P II] 1.188 μ m ratios of NLRs (NGC 4151 by Storchi-Bergmann et al. 2009 and Mrk 1066 by Riffel et al. 2010), similar results were reported in both cases. Storchi-Bergmann et al. (2009) found that [Fe II] 1.257 μ m/[P II] 1.188 μ m ratios are higher at ~ 130 pc away from the nucleus of NGC 4151 (~ 6) than that in its nucleus (~ 2). They also pointed out a possible spatial correlation between [Fe II] 1.257 μ m/[P II] 1.188 μ m and radio continuum structure. They suggested that shocks induced by a radio jet release the Fe locked in grains and produce an enhancement of the [Fe II] emission at off nucleus regions. Similarly Riffel et al. (2010) found that Mrk 1066 presents [Fe II] 1.257 μ m/[P II] 1.188 μ m ~ 3 at most locations within ~ 470 pc from the nucleus, but in some regions close to the borders of the radio continuum structure this ratio reaches values up to 9.5. They concluded that shocks seem to play a more important role in these regions.

Figure 3b shows VLA 4.86 GHz flux density as a function of distance from the nucleus of NGC 1068 extracted from a same slit aperture as our near-infrared observation with OAO/ISLE. The radio data was obtained from NRAO Science Data Archive.¹ At off nucleus region of NGC 1068

¹ (<https://archive.nrao.edu/archive/e2earchivex.jsp>).

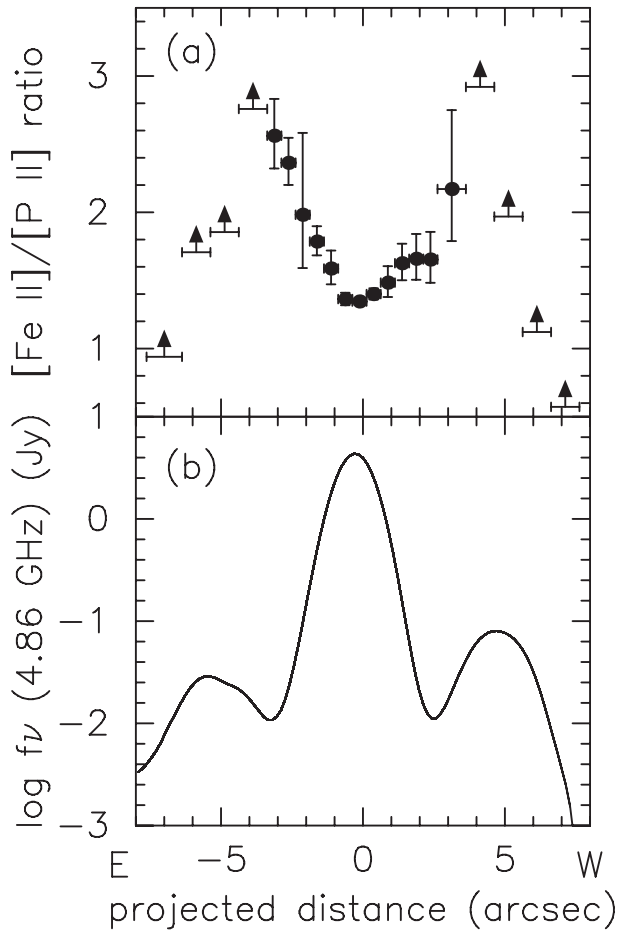


Fig. 3. [Fe II] 1.257 μm /[P II] 1.188 μm line ratio (top) and VLA 4.86 GHz flux density (bottom) as a function of distance from a continuum peak. Arrows in the top figure are lower limits calculated from 3σ noise level around undetected [P II] 1.188 μm .

we find a possible association between [Fe II] 1.257 μm /[P II] 1.188 μm and the radio continuum like NGC 4151 and Mrk 1066. The higher ratios at off nucleus of NGC 1068 is likely attributed to a mild contribution of shock ionization to ionized gases. This may indicate that the interaction between the jet and ISM forms an expanding cocoon which induces the

shock waves propagating perpendicularly in the direction of the jet axis (e.g., Scheuer 1974), while photoionization by central engine is dominant near the nucleus.

5. Conclusion

The line ratio [Fe II] 1.257 μm /[P II] 1.188 μm in the near-infrared wavelength range is a useful tool with which to examine the dust destruction by shocks. We investigated spatial distribution of this ratio in NLR of nearby Seyfert galaxy NGC 1068 with OAO/ISLE. [Fe II] 1.257 μm /[P II] 1.188 μm near the nucleus is close to unity consistent with a previous observation and with a ratio in a normal photoionized region. This indicates that photoionization by ionizing photons radiating from a central engine is dominant near the nucleus. We found that the ratio increases with the distance from the nucleus, and is slightly higher at 3''–4'' east and west of the nucleus than ratios typical of a photoionized region. We also found a possible spatial association between [Fe II] 1.257 μm /[P II] 1.188 μm and radio continuum around ~ 560 from the nucleus. These findings suggest a higher contribution of shock ionization induced by a radio jet at off nucleus. Except for NGC 1068, recently the spatial correlation between [Fe II] 1.257 μm /[P II] 1.188 μm and radio continuum over the several hundred parsec scale has been reported for NGC 4151 and Mrk 1066. Applying this kind of research to a number of other AGNs is the clue to revealing ongoing AGN feedback phenomena.

We would like to thank Nozomu Kawakatu for his meaningful comments on interpretation of observed data. This work was supported by the Publications Committee of the National Astronomical Observatory of Japan (NAOJ) and the Grant-in-Aid for the Global COE Program "The Next Generation of Physics, Spun from Universality and Emergence" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. T.N. acknowledges financial supports through the Research Promotion Award of Ehime University and the Kurata Memorial Hitachi Science and Technology Foundation. K.M. acknowledges financial support from the Japan Society for the Promotion of Science (JSPS) through the JSPS Research Fellowships for Young Scientists.

References

- Allen, M. G., Groves, B. A., Dopita, M. A., Sutherland, R. S., & Kewley, L. J. 2008, *ApJS*, 178, 20
- Bower, R. G., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2006, *MNRAS*, 370, 645
- Capetti, A., Axon, D. J., & Macchetto, F. D. 1997, *ApJ*, 487, 560
- Crenshaw, D. M., Schmitt, H. R., Kraemer, S. B., Mushotzky, R. F., & Dunn, J. P. 2010, *ApJ*, 708, 419
- Croton, D. J., et al. 2006, *MNRAS*, 365, 11
- Das, V., Crenshaw, D. M., Kraemer, S. B., & Deo, R. P. 2006, *AJ*, 132, 620
- Dopita, M. A., & Sutherland, R. S. 1995, *ApJ*, 455, 468
- Dopita, M. A., & Sutherland, R. S. 1996, *ApJS*, 102, 161
- Fu, H., & Stockton, A. 2007, *ApJ*, 666, 794
- Kriss, G. A. 1994, in *ASP Conf. Ser.*, 61, *Astronomical Data Analysis Software & Systems III*, ed. D. R. Crabtree et al. (San Francisco: ASP), 437
- Krueger, T. K., & Czyzak, S. J. 1970, *Proc. R. Soc. London, Ser. A*, 318, 531
- Mendoza, C., & Zeppen, C. J. 1982, *MNRAS*, 199, 1025
- Nagao, T., Maiolino, R., & Marconi, A. 2006, *A&A*, 447, 863
- Nussbaumer, H., & Storey, P. J. 1988, *A&A*, 193, 327
- Oliva, E., et al. 2001, *A&A*, 369, L5
- Osterbrock, D. E. 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Mill Valley, CA: University Science Books), 422
- Riffel, R. A., Storchi-Bergmann, T., & Nagar, N. M. 2010, *MNRAS*, 404, 166

- Scannapieco, E., Silk, J., & Bouwens, R. 2005, ApJ, 635, L13
Scheuer, P. A. G. 1974, MNRAS, 166, 513
Sijacki, D., Springel, V., Di Matteo, T., & Hernquist, L. 2007, MNRAS, 380, 877
Storchi-Bergmann, T., McGregor, P. J., Riffel, R. A., Simões Lopes, R., Beck, T., & Dopita, M. 2009, MNRAS, 394, 1148
Walmsley, C. M., Natta, A., Oliva, E., & Testi, L. 2000, A&A, 364, 301
Wilson, A. S., & Ulvestad, J. S. 1983, ApJ, 275, 8
Yanagisawa, K., et al. 2008, Proc. SPIE, 7014, 701437
Yanagisawa, K., Shimizu, Y., Okita, K., Nagayama, S., Sato, Y., Koyama, H., Okada, T., & Iwata, I. 2006, Proc. SPIE, 6269, 62693Q
Zhang, H. L., & Pradhan, A. K. 1995, A&A, 293, 953