DOES THE RADIATIVE AVALANCHE FUELING WORK IN ANY ACTIVE GALACTIC NUCLEI?

YOSHIKI TANIGUCHI
Astronomical Institute, Tohoku University, Aoba, Sendai 980-77, Japan
Received 1997 April 28; accepted 1997 July 16

ABSTRACT
Recently Umemura, Fukue, & Mineshige proposed radiative avalanche fueling to active galactic nuclei, viz., gas accretion is driven by the radiation drag exerted by stellar radiation from circumnuclear starburst regions. This mechanism is also interesting in terms of starburst-AGN connections. We here present observational tests for radiative avalanche fueling. Our tests, however, show that gas accretion rates driven by the radiative avalanche are significantly lower than those expected from the standard accretion theory applied to typical active galactic nuclei with circumnuclear starburst regions. We thus propose an alternative, possible starburst-AGN connection, viz., a minor merger with a nucleated satellite drives circumnuclear starbursts which leads to gas fueling onto the central engine as the merger proceeds.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: nuclei — quasars: general

1. INTRODUCTION
Starburst activity is observed in the circumnuclear regions of some active galactic nuclei (AGNs), and possible starburst-AGN connections have been discussed for two decades (Weedman 1983; Terlevich & Melnick 1985; Norman & Scoville 1988; Sanders et al. 1988; Heckman et al. 1989; Rieke 1992; Scoville 1992; Taniguchi 1987, 1992; Mouriri & Taniguchi 1992; Terlevich et al. 1992). Several mechanisms have been discussed: starburst-driven formation of compact nuclei (e.g., Weedman 1983); AGN modeling without a supermassive black hole (e.g., Terlevich et al. 1992); and gas fueling triggered by the circumnuclear starbursts (e.g., Norman & Scoville 1988; Taniguchi 1992).

Recently, Umemura, Fukue, & Mineshige (1997a, 1997b; hereafter UFM97a and UFM97b, respectively) proposed the novel idea that gas accretion onto a supermassive black hole may be triggered by the radiation drag exerted by stellar radiation from the circumnuclear starburst regions (the radiative avalanche fueling), based on a well-known physical process, the Poynting-Robertson effect. Since it is known that a number of AGNs have actually luminous circumnuclear starbursts (hereafter CNSB) regions (see, e.g., Telesco et al. 1984; Heckman et al. 1986; Keel 1987; Wilson 1988; Storchi-Bergmann et al. 1996a, 1996b, and references therein), it is worth testing if this new mechanism works from an observational point of view.

2. A BRIEF SUMMARY OF THE RADIATIVE AVALANCHE FUELING
We give a brief summary of the radiative avalanche fueling proposed by UFM97a and UFM97b. The radiative avalanche means that gas accretion is driven by the radiation drag exerted by stellar radiation from circumnuclear starburst regions. If a surface layer of a rotating nuclear gas disk is irradiated by the massive stars in the CNSB regions, the gas on the surface could lose angular momentum via radiation drag (i.e., Poynting-Robertson effect; Poynting 1903; Robertson 1937), giving rise to an avalanche of the gas layer.

If a CNSB region with a total luminosity $L_{\text{CNSB}}$ is located at radius $R$ with an effective size $\Delta R$ (i.e., the effective diameter of a star-forming clump), the accretion rate that is due to the avalanche at a radius $r(<R)$ is given by

$$M_{\text{rad}} \approx 0.2\eta_s \sin \theta_s \left( \frac{r}{R} \right)^2 \left( \frac{L_{\text{CNSB}}}{3 \times 10^{12} L_\odot} \right) M_\odot \text{yr}^{-1},$$

(1)

where $\eta_s$ is the efficiency of radiative accretion ($\sim 0.1–1$) and ($\sin \theta_s$) $(r/R)^2$ is the irradiation efficiency onto the surface layer at radius $r$, where $\sin \theta_s \sim \Delta R/(R - r)$. In the following discussion, we adopt $\eta_s = 1$. In UFM97a and UFM97b, the factor of $\sin \theta_s$ is not seriously taken into account. However, recent Hubble Space Telescope observations have shown that the CNSB regions consist of a number of star-forming clumps and each clump (i.e., a star cluster) has an effective diameter of at most $\sim 10$ pc (Barth et al. 1995; Maoz et al. 1996). This compact nature is also observed in the archetypical giant H II region, 30 Dor in LMC (Weigelt et al. 1991). Given the typical radius of 1 kpc for the CNSB rings (Storchi-Bergman et al. 1996a, 1996b), we estimate $\sin \theta_s \sim 0.01$. Furthermore, the geometrical dilution factor is estimated to be $(r/R)^2 \sim 0.01$ for $r = 100$ pc and $R = 1$ kpc. Therefore, the accretion rate driven by the radiative avalanche is much lower than that estimated in UFM97a and UFM97b.

The characteristic accretion timescale for the radiative avalanche is estimated as

$$t_{\text{rad}} \approx 2.4 \times 10^6 \left( \frac{L_{\text{CNSB}}}{3 \times 10^{12} L_\odot} \right)^{-1} \left( \frac{R}{100 \text{ pc}} \right)^2 \left( \frac{f_{\text{d}}} {10^{-2}} \right)^{-1} \times \left( \frac{a_d}{0.1 \mu\text{m}} \right) \left( \frac{\rho_s}{\text{g cm}^{-3}} \right) \text{yr},$$

(2)

where $f_{\text{d}}$ is the dust-to-gas mass ratio, $a_d$ is the size of dust grains, and $\rho_s$ is the mass density of solid material within the grain. The CNSBs in AGNs are usually observed as ringed (or armed) star-forming clumps, and their typical radii range from several 100 pc to 1 kpc (Telesco et al. 1984; Boer & Schulz 1993; Genzel et al. 1995; Storchi-Bergmann et al. at 1996, 1996b; Maoz et al. 1996). The luminosities of the CNSBs are $\sim 10^{11} L_\odot$ in both NGC 1068 (e.g., Telesco et al. 1984) and NGC 7469 (e.g., Genzel et al. 1995). If we adopt $L_{\text{CNSB}} = 10^{11} L_\odot$ and $R = 1$ kpc, we obtain $t_{\text{rad}} \sim 7 \times 10^6$ yr. This timescale seems too...
long to cause efficient fueling to AGN, although the ages of the CNSBs in Seyfert galaxies have been estimated to be $\sim 10^8$ yr, being significantly older than the ages of ongoing starbursts, which are $\sim 10^7$ yr (Glass & Moorwood 1985; Mouri & Taniguchi 1992; Taniguchi & Mouri 1992; Dultzin-Hacyan & Benitez 1994; Oliva et al. 1995; Hunt et al. 1997).

3. OBSERVATIONAL TESTS FOR THE RADIATIVE AVALANCHE FUELING

3.1. Circumnuclear Starbursts around Seyfert Nuclei

Before presenting the observational tests for radiative avalanche fueling, we consider arguments for the occurrence of the CNSBs around Seyfert nuclei. Using the IRAS database, several researchers have suggested that Seyfert 2 nuclei (hereafter S2s) tend to show excess mid- (MIR) and far-infrared (FIR) emission with respect to Seyfert 1 galaxies (S1s) (Rodríguez-Espinosa, Rudy, & Jones 1987; Dahari & De Robertis 1988; Heckman et al. 1989; Maiolino et al. 1995). Also, molecular gas content is higher in S2s than in S1s (Heckman et al. 1989). These observations are usually interpreted as meaning that S2s tend to have luminous CNSB regions more often than S1s. However, if there are extended dusty clouds around Seyfert nuclei, they would show excess emission at FIR because the equilibrium temperature is as cold as 100 K (Pier & Krolik 1993; Granato, Danese, & Francheschini 1996; Taniguchi et al. 1997). This means that S2s may have brighter FIR emission if they have more extended dusty regions around their nuclei. Thus we cannot conclude solely from the analysis of FIR data that almost all S2s have the CNSB.

Pogge (1989) made a narrow-band emission-line imaging survey of 20 nearby Seyfert galaxies and found that the CNSB regions are present only in $\sim 30\%$ of the S2s while no CNSB is found in the S1s. Although there is a famous S1 with an intense CNSB, viz., NGC 7469 (Heckman et al. 1986; Wilson et al. 1986, 1991; Keto et al. 1992; Mauder et al. 1994; Genzel et al. 1995), it is known that there are few S1s with CNSBs (Oliva et al. 1995; Hunt et al. 1997). Hunt et al. (1997) showed from their NIR multicolor imaging study that there is little evidence for CNSBs in S1s and that, even if CNSB events did occur in them, they occurred more than $10^8$ yr ago. Thus we conclude that the radiative avalanche triggered by the CNSBs cannot work in most S1s in the nearby universe because of the absence of CNSBs in them. Therefore, possible candidates of Seyfert nuclei triggered by the radiative avalanche may be about one-third of S2s and a few S1s which have the luminous CNSBs around the nuclei. In the following subsections, we present observational tests for typical Seyfert and LINER1 nuclei with CNSBs. We also mention the case of ultraluminous infrared galaxies (Sanders et al. 1988).

3.2. Seyfert Nuclei with Luminous Circumnuclear Starbursts

Among the Seyfert nuclei with CNSBs (Storchi-Bergmann et al. 1996a, 1996b, and references therein), we study the two archetypical Seyfert nuclei, NGC 1068 (S2) and NGC 7469 (S1). In order to determine if the gas accretion driven by the radiative avalanche is high enough to achieve the observed bolometric luminosities of central engines, we compare two accretion rates: (1) the gas accretion rate driven by radiative avalanche that is due to the stellar lights from the CNSBs (see eq. [1]), and (2) the gas accretion rate estimated using the standard accretion theory (Rees 1984),

$$M_{\text{acc}} = \frac{L_{\text{bol}}}{h \eta_{\text{acc}} c^2} \approx 0.02 \left( \frac{L_{\text{bol}}}{10^{45} \text{ ergs s}^{-1}} \right) \left( \frac{\eta_{\text{acc}}}{0.1} \right)^{-1} M_{\odot} \text{ yr}^{-1},$$

(3)

where $\eta_{\text{acc}}$ is the conversion efficiency from the gravitational energy to the radiation. As for AGNs with CNSBs, UFM97a and UFM97b concluded that only high-energy photons come from the central engine, while the other radiation (e.g., from FIR to UV) comes from the CNSBs. Thus they used X-ray luminosity instead $L_{\text{bol}}$ when they estimated $M_{\text{acc}}$. However, this assumption seems to be inadequate. The reason for this phenomenon is that much of the infrared emission of such galaxies comes from the dusty tori (Pier & Krolik 1993; Pier et al. 1994; for the extreme case see Taniguchi et al. 1997). Therefore, in the later discussion, we use the $L_{\text{bol}}$ values derived from the spatially resolved observations in the estimates of $M_{\text{acc}}$. Also, we use the CNSB luminosities based on the spatially resolved observations in the estimates of $M_{\text{rad}}$. Our method makes it possible to perform accurate tests.

NGC 1068 is one of the most luminous Seyfert galaxies in the local universe. The bolometric luminosity of the central engine is estimated to be $L_{\text{bol}} = 8.5 \times 10^{44} (f_{\text{rad}}/0.1)^{-1/2}(D/22 \text{ Mpc})^2$ ergs s$^{-1}$, where $f_{\text{rad}}$ is the fraction of nuclear flux reflected into our line of sight and $D$ is the distance to NGC 1068 (Pier et al. 1994). Adopting the fiducial values in Pier et al. (1994), we obtain the gas accretion rate, $M_{\text{acc}} \approx 0.17 M_{\odot} \text{ yr}^{-1}$. Next, we estimate the accretion rate driven by the radiative avalanche. The bolometric luminosity of the CNSB regions is estimated to be $L_{\text{CNSB}} \approx 2.2 \times 10^{41} L_{\odot}$ at a distance of 22 Mpc (Telesco et al. 1984). The radius of the CNSB ring is about 1 kpc (Telesco et al. 1984; Baldwin et al. 1987). Although there is no direct measurement of the vertical width ($\Delta R$) of the star-forming clumps, it is estimated to be at most 10 pc (Weigelt et al. 1991; Barth et al. 1995; Maoz et al. 1996). If we consider the radiative avalanche at $r = 100$ pc, the irradiation efficiency is given by $\eta_{\text{rad}}/\eta_{\text{acc}} \approx \Delta R r / [(R - r)R^2] \approx 1.1 \times 10^{-4}$. We thus obtain the accretion rate by radiative avalanche, $M_{\text{rad}} \approx 1.6 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ for $r = 100$ pc. Since this accretion rate is much lower than that estimated from the accretion theory, we conclude that the radiative avalanche does not work in NGC 1068.

NGC 7469 is another of the famous Seyfert galaxies with luminous CNSB regions (Cutri et al. 1984; Heckman et al. 1986; Wilson et al. 1986, 1991; Miles, Houck, & Hayward 1994; Mauder et al. 1994; Genzel et al. 1995). The bolometric luminosity of the central engine including the stellar luminosity of the host galaxy is $8.9 \times 10^{43}$ ergs s$^{-1}$ at a distance of 98 Mpc (Genzel et al. 1995). Since the contribution of the central engine to this luminosity is $\sim 40\%$ (Kotilainen et al. 1992), we obtain $L_{\text{rad}} \approx 3.5 \times 10^{43}$ ergs s$^{-1}$, and thus the required gas accretion rate is $M_{\text{rad}} \approx 0.07 M_{\odot} \text{ yr}^{-1}$. On the other hand, the CNSB ring has the luminosity of $4.5 \times 10^{31} L_{\odot}$ at a radius of 720 pc. Assuming $\Delta R = 10$ pc again, we obtain $M_{\text{rad}} \approx 9.3 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ for $r = 100$ pc, which is much lower than the

1 LINER = Low Ionization Nuclear Emission-line Region (Heckman 1980).

2 Braatz et al. (1993) and Cameron et al. (1993) detected an inner MIR component with size $\sim 100$ pc. Since, however, the dusty torus in NGC 1068 is thought to be extended at radius of 100 pc (Pier & Krolik 1993), this MIR component may not be the star-forming region. Even if this component is the star-forming region, the accretion rate by radiative avalanche is still smaller by one order of magnitude than the predicted value.
expected value. Accordingly, we have shown that the contribution of the gas accretion driven by radiative avalanche is negligibly small in both the Seyfert nuclei, NGC 1068 and NGC 7469.

3.3. LINERs with Circumnuclear Starbursts

It is also known that some LINERs have CNSBs (Storchi-Bergmann et al. 1996a, 1996b, and references therein). Here we investigate the case of NGC 1097 (Keel 1983; Hummel, van der Hulst, & Keel 1987; Storchi-Bergmann, Baldwin, & Wilson 1993; Storchi-Bergmann et al. 1995; Barth et al. 1995). Although this galaxy was originally classified as a LINER (Keel 1983), the double-peaked broad line emission has appeared since 1991 (Storchi-Bergmann et al. 1993, 1995). In terms of the standard model, some sporadic accretion events have occurred since 1991 (Eracleous et al. 1995). It is interesting to consider if this accretion is due to the radiative avalanche. Although there is no measurement of the bolometric luminosity of the central engine, using the observed Hα luminosity of the broad line component, $L(\text{H}α) = 5.5 \times 10^{39}$ ergs s$^{-1}$ at a distance of 14.5 Mpc (Storchi-Bergmann et al. 1993), we estimate $L_{\text{rad}} \sim 100L(\text{H}α) \approx 5.5 \times 10^{41}$ ergs s$^{-1}$ (Ward et al. 1987; H. Mouri, private communication). Thus we obtain the gas accretion rate $\dot{M}_{\text{gas}} \approx 1.1 \times 10^{-4} M_\odot$ yr$^{-1}$. Taking the semiminor radius of the CNSB ring to be 650 pc, the width of the ring to be 5 pc (Barth et al. 1995), and $L_{\text{CNSB}} = 4.9 \times 10^7 L_\odot$ (Hummel et al. 1987), we obtain $\dot{M}_{\text{rad}} \approx 1.4 \times 10^{-9} M_\odot$ yr$^{-1}$ for $r = 100$ pc. Since this rate is much lower than the expected value, we conclude that the radiative avalanche does not work in NGC 1097.

3.4. Ultraluminous Infrared Galaxies

Our final test is applied to the ultraluminous infrared galaxies (ULIGs; Sanders et al. 1988). Because of the huge bolometric luminosities of the starbursts, $L_{\text{CNSB}} \sim 10^{12} L_\odot$ and the compact nature of the starbursts, $R \sim 50$ pc (Condon et al. 1991), the radiative avalanche would work most efficiently in the ULIGs. Since it is likely that the ULIG nuclei are surrounded by the CNSB regions (i.e., the geometrical dilution factor $\sim 1$), we obtain $\dot{M}_{\text{rad}} \approx 0.07 M_\odot$ yr$^{-1}$. It is here noted that the circumnuclear molecular gas mass in ULIGs is typically $\sim 10^{10} M_\odot$ (Scoville et al. 1991). If this gas is supplied to the nuclear region within a merger timescale of $\sim 10^6$ yr, the average gas accretion rate comes to $\sim 10 M_\odot$ yr$^{-1}$. In fact, many numerical simulations have shown that major mergers between two gas-rich galaxies can supply a large amount of gas within a reasonable timescale (Mihos & Hernquist 1994b, and references therein). Since this rate is much higher than that from the radiative avalanche, we consider that the dynamical accretion driven by the merger is the dominant fueling mechanism rather than the radiative avalanche.

4. DISCUSSION: AN ALTERNATIVE STARBURST-AGN CONNECTION

Although we have shown that radiative avalanche fueling may not work in actual AGNs, it is still worth discussing possible starburst-AGN connections because a nonnegligible number of AGNs indeed have the CNSBs. We therefore consider another possible connection in this section.

Given the standard scenario for AGNs, gas fueling is one of the most important physical processes for triggering AGNs (Shlosman, Begelman, & Frank 1990). For Seyfert nuclei,\(^3\) possible fueling mechanisms are tidal triggering by a companion galaxy (Noguchi 1988; for a review, see Barnes & Hernquist 1992) or a minor merger with a satellite galaxy (Gaskell 1985; Mihos & Hernquist 1994a; Hernquist & Mihos 1995). Although Seyfert galaxies tend to have companion galaxies, the percentage of Seyfert galaxies with physical companions is at most 12% (Rafanelli, Violato, & Baruffolo 1995, and references therein). Further, there is no preferred kind of interaction (prograde, polar, or retrograde) among the Seyfert galaxies with physical companions (Keel 1996), although efficient fueling would occur in prograde interacting systems. Therefore, the majority of Seyfert galaxies have no relation with tidal interaction and thus should be triggered by certain internal mechanisms. On the other hand, since most galaxies have their satellite galaxies (Zaritsky et al. 1997, and references therein), it is likely that they have already experienced some minor mergers during their lives (Ostriker & Tremaine 1975; Tremaine 1981). Hence it is suggested strongly that the minor merger hypothesis has a great advantage over tidal triggering.

Here we propose a new possible starburst-AGN connection based on the minor merger hypothesis. Recently, Taniguchi & Wada (1996) argued that a minor merger with a "nucleated" satellite causes efficient gas fueling, leading first to circumnuclear starbursts and then to nuclear starbursts, because of the dynamical disturbance driven by a supermassive binary (i.e., the host nucleus and the satellite nucleus) during the course of the minor merger. If a host galaxy disk has abundant gas, a circumnuclear gas disk would be formed prior to the attack by the satellite nucleus (Hernquist & Mihos 1995). Therefore, if this is the case, a circumnuclear starburst would occur in an early stage of the supermassive binary formation. As the separation between the nuclei decreases, the gas clouds are channeled gradually into the host nucleus during the course of merger evolution. The merger timescale from a radius of $\sim 1$ kpc to the nuclear region may be of order $10^9$ yr (Taniguchi & Wada 1996). Accordingly, we are able to explain the simultaneous presence of both older CNSB regions and the fueled AGNs; i.e., Seyfert nuclei with CNSBs; the majority may be S2s). On the other hand, if a host galaxy disk has little gas, no CNSB would occur, but the central engine would be fueled finally because any disk galaxies may have a bit of nuclear gas\(^4\) (e.g., Taniguchi et al. 1994), giving rise to S1s with no CNSB. Therefore, a variety of Seyfert nuclei can arise as due to different gaseous contents in the hosts.

It seems hard to detect direct evidence for minor mergers in some cases because the dynamical perturbation should be significantly smaller than that of typical galaxy interaction. The long timescale of the merger, $\sim 10^9$ yr, may lead to the smearing of the relic of minor mergers. Thus some well-evolved minor mergers may be observed as ordinary-looking isolated galaxies. However, it is known that minor mergers cause the kinematic heating of host disks (Quinn, Hernquist, & Fullagar 1993). Such disk galaxies may be classified as S0 or amorphous galaxies which are frequently observed in the Seyfert hosts (Simkin, Su, & Schwarz 1980; MacKenty 1990).

\(^3\) Ho, Filippenko, & Sargent (1997) show that bars have a negligible effect on the strength of AGNs in their sample of over 300 spiral galaxies. Therefore, we do not believe that the gas fueling driven by bars is important.

\(^4\) Typical Seyfert nuclei need gas of $\sim 10^6 M_\odot$ as the fuel to sustain the central engine if the accretion rate is $\sim 0.01 M_\odot$ yr$^{-1}$ and the duration of active phase is $10^9$ yr.
Therefore, the minor merger hypothesis can also explain the observed diversity in the morphological properties of Seyfert hosts (Simkin et al. 1980; Arsenault 1989; MacKenty 1990; Moles, Marquez, & Perez 1995). It is also interesting to note that the minor merger hypothesis can also be responsible for the observed random orientation of radio jets in Seyfert nuclei with respect to the host disk axis as discussed by Schmitt et al. (1997, and references therein). Finally, we mention that the merger scenario is also applicable to the more luminous starburst-AGN (i.e., ULIG-quasar) connection, provided that major mergers between or among nucleated gas-rich galaxies are progenitors of quasars (Sanders et al. 1988).

We would like to thank Masayuki Umemura, Jun Fukue, Shin Mineshige, Keiichi Wada, Toru Yamada, Hideaki Moura, and Neil Trentham for useful discussion and comments. This work was financially supported in part by Grant-in-Aids for the Scientific Research (No. 0704405) of the Japanese Ministry of Education, Culture, Sport, and Science.

REFERENCES

Arsenault, R. 1989, A&A, 217, 66
Baldwin, J. A. 1981, in Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko (San Francisco: ASP), 61
Lawrence, A. 1987, ApJ, 315, 74

Pogge, R. W. 1989, ApJ, 345, 730
Poyning, J. H. 1993, Phil. Trans. Roy. Soc. London, A, 202, 525
Quinn, P. J., Hernquist, L., & Fullagar, D. P. 1993, ApJ, 403, 74
Rafanelli, P., Violato, M., & Baruffolo, A. 1995, AJ, 109, 1546
Rees, M. J. 1984, ARA&A, 22, 471

Rieke, G. H. 1992, in Proc. ASP Conf. Ser. 31, Relationships between Active Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko (San Francisco: ASP), 159
Sevc, N. Z., Sargent, A. I., Sanders, D. B., & Soifer, B. T. 1991, ApJ, 466, L5
Shlosman, I., Begelman, M. C., & Frank, J. 1990, Nature, 345, 679
Simkin, S. M., Su, H. S. T., & Schwarz, M. P. 1980, ApJ, 237, 404
Storchi-Bergmann, T., Baldwin, J. A., & Wilson, A. S. 1993, ApJ, L11
Storchi-Bergmann, T., Eracleous, M., Livio, M., Wilson, A. S., & Filippenko, A. V., & Halpern, J. P. 1995, ApJ, 443, 617
Storchi-Bergmann, T., Rodriguez-Ardila, A., Schmitt, H. R., Wilson, A. S., & Baldwin, J. A. 1996b, ApJ, 472, 83
Storchi-Bergmann, T., Wilson, A. S., & Baldwin, J. A. 1996a, ApJ, 460, 252

Taniguchi, Y. 1987, ApJ, 317, L57
—. 1992, in Proc. ASP Conf. Ser. 31, Relationships between Active Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko (San Francisco: ASP), 357
Taniguchi, Y., & Mouri, H. 1992, in Proc. ASP Conf. Ser. 31, Relationships between Active Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko (San Francisco: ASP), 365
Taniguchi, Y., Murayama, T., Nakai, N., Suzuki, M., & Kamaya, O. 1994, AJ, 108, 468
Taniguchi, Y., Sato, Y., Kawara, K., Murayama, T., & Mouri, H. 1997, A&A, 318, L1

TANIGUCHI

...