EXTENDED MULTIWAVELENGTH FUZZ AROUND RED QUASARS: THE OBSERVATIONAL APPEARANCE OF RADIATIVE FEEDBACK IN ACTION

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1. INTRODUCTION

Red quasars are a population characterized by significant extinction in UV, which could be explained by absorption of dusty gas on a scale of a few kpc. We show that the enhanced radiation pressure drives the dusty gas to supersonically expand and produces shocks. The shocks energize electrons to be relativistic via the first Fermi acceleration. As a balance of shock acceleration and synchrotron emission and inverse Compton scattering, the maximum Lorentz factor of the electrons reaches $\sim 10^6$. The shocked interstellar medium appears as extended multiwavelength fuzz, in which synchrotron emission from the electron peaks at near-infrared or UV bands and inverse Compton scattering around 1.0 GeV–0.1 TeV. Future multiwavelength images of the fuzz would provide new clues to study the details of radiative feedback if red quasars are a certain phase in the evolutionary chains of galaxies.

Subject headings: black hole physics — galaxies: evolution — quasars: general

1. INTRODUCTION

Radiative feedback from quasars to the surroundings of their hosts has been realized for many years. Several effects have been suggested, including Compton heating (Begelman 1985; Chang et al. 1987; Wang et al. 2005), acoustic wave heating (Chelouche 2008), and proximity effects (Baytlik et al. 1988; Gonçalves et al. 2008; Wild et al. 2008; Prochaska & Hennawi 2008). The strong feedback due to radiation may quench the inflows fueling the central black hole (e.g., Binney & Tabor 1995) and star formation so as to raise the relation between black hole masses and dispersion velocities (Silk & Rees 1998; King 2003; Ciotti & Ostriker 2007; Fabian et al. 2006). However, the direct large-scale evidence for feedback is scarce, and even absent in most cases.

Traditionally quasars are selected based on their bluer color; however, the existence of a significant population of red quasars has been the subject of debate for a number of years. The percentage of red quasars is only $\sim 6\%$ or so from the large database of the Sloan Digital Sky Survey (SDSS) (Richards et al. 2003), $\sim 20\%$–$30\%$ in the FIRST-MASS red quasar survey (Glikman et al. 2007), and $\sim 20\%$–$30\%$ in the Spitzer survey (Brown et al. 2006; Lacy et al. 2007). The fraction of red quasars remains a big debate; however, this might be due to heterogeneous definition or selection effects of surveys. There is increasing evidence for dust extinction as one of the major explanations for red quasars from the SDSS (Richards et al. 2003), GALEX data (Trammell et al. 2007), the Spitzer survey (Brown et al. 2006; Lacy et al. 2007), and HST images (Urrutia et al. 2008), as well as from numerical simulations (Di Matteo et al. 2005; Hopkins et al. 2007). The debris, ejected from mergers or starburst triggering the central black holes, surrounds the nucleus prior to the galactic winds (Sanders et al. 1988; Yun et al. 2004; Fabian et al. 2006; Hopkins et al. 2007), reddening quasars. The well-known roles of dust particles in outflows, as results of strong coupling between the charged grains with gas (e.g., Draine & Salpeter 1979), have been realized in the dynamics of dusty gas (Chang et al. 1987; Murray et al. 2005; Fabian et al. 2006). It is then expected that the medium swept by quasar radiation results in the extinction of quasars.

The present Letter makes an attempt to connect the action of radiative feedback to the phenomena of red quasars and predicts some observational features. We argue that radiation from quasars is partly converted to the kinetic luminosity of supersonic outflowing gas and then partly transformed to the kinetic energy of accelerated electrons via the Fermi mechanism, producing extended fuzz with nonthermal emission from the radio to $\gamma$-rays around red quasars.

2. DYNAMICS OF DUSTY GAS

Dusty winds in homogeneous medium have been discussed in the literature (Chang et al. 1987; Murray et al. 2005; Fabian et al. 2006). On the other hand, the gas in dark matter halos is driven into two phases in temperature by the thermal instability (Fall & Rees 1985), especially in the presence of radiation heating of quasars. Thermal states of the medium are not the main goals of this Letter, but we will discuss two cases of the medium: (1) homogeneous interstellar medium (ISM) and (2) clumpy ISM. The observational appearance of the extended fuzz is quite similar for the two cases unless the high spatial resolution of radio telescopes could resolve the cold clouds.

2.1. Homogeneous ISM

For an isothermal sphere of gas with density profile $\rho \propto R^{-2}$, Murray et al. (2005) show the velocity of the momentum-driven winds at $R$ for the optically thin limit

$$V(R) = 2\sigma \left(\frac{L}{L_{\text{Edd}}} \right) \left(1 - \frac{R_{\text{exp}}}{R}\right) + \ln \left(\frac{R_{\text{exp}}}{R}\right)^{1/2},$$

from equation (26) in Murray et al. (2005), where $R$ is the radius of the expanding winds, $R_{\text{exp}} = \sigma^2 \sigma_T / 2\pi G M_p \approx 123 \sigma_{200}^2$ pc is the initial radius of the winds (Fabian et al. 2006), $\sigma$ is the dispersion velocity ($\sigma = 200 \sigma_{200}$ km s$^{-1}$), $L_{\text{Edd}} = 2.07 \times 10^{46} \sigma_{200}^2$ ergs s$^{-1}$ is the Eddington luminosity, and $\sigma_T$ is the Thompson cross section.

Here we only consider graphite grains and assume they are spherical with a radius $a$. We assume the ISM has the same gas-to-dust ratio with the Galaxy. Since the charged particles of dust are strongly coupled with the ionized atoms via Cou-
lomb interaction (Draine & Salpeter 1979), the dusty gas feels a stronger radiation pressure, amplified by a factor of

$$A = \frac{\sigma_v}{\sigma_T} = 4.7 \times 10^3 a_{-5}^2,$$

(2)

where $$\sigma_v = 3.1 \times 10^{-27} a_{-5}^2 \text{ cm}^{-2}$$ is the mean cross section per hydrogen atom for UV photons in the presence of dust (Martin & Ferland 1980; Chang et al. 1987; Fabian et al. 2006) and $$a_{-5} = a/10^{-5} \text{ cm}.$$ The factor $$A$$ has been discussed for various cases in detail by Fabian et al. (2006). For dusty gas, the Eddington limit in equation (1) should be replaced by $$L_{\text{Edd}} = L_{\text{Edd}}/A.$$ For a quasar with a bolometric luminosity $$L_{\text{bol}}$$, the UV luminosity is approximately $$L_{\text{UV}} = \xi L_{\text{bol}} = \xi \lambda L_{\text{Edd}}$$, where $$\xi \approx 0.1$$ (Marconi et al. 2004) and $$\lambda$$ is the Eddington ratio. Inserting $$L_{\text{Edd}}$$ into equation (1), we have the maximum velocity of the expansion

$$V_{\text{max}} = 2\sigma_v a \lambda \xi - \ln(\lambda \xi) - 1 \approx 13.4\sigma_v A_{500} (\lambda \xi_{0.1})^{1/2}$$

(3)

at the radius

$$R_{\text{max}} = A \lambda \xi R_{\text{exp}} \approx 6.0 A_{500} \xi_{0.1}^2 a_{200}^2 \text{ kpc},$$

(4)

and the Mach number is

$$M_{\text{max}} = V_{\text{max}}/c_s = 93.4 A_{500} (\lambda \xi_{0.1})^{1/2} T_5^{-1/2},$$

(5)

where $$A_{500} = A/500,$$ $$\xi_{0.1} = \xi/0.1,$$ $$c_s = 2.87 \times 10^6 T_5^{1/2} \text{ cm s}^{-1}$$ is the sound speed and $$T_5 = T/10^5 \text{ K.}$$ Here we assume warm winds with a temperature of $$10^5 \text{ K.}$$ The supersonic winds form shocks inevitably and the strongest shocks are at $$R_{\text{max}} \approx 6.0 \text{ kpc.}$$ It should be noted that the velocity from equation (1) is insensitive to the radius after $$R_{\text{max}},$$ implying that strong shocks still extend farther. Chang et al. (1987) showed that shocks appear in both one- and two-dimension flows by detailed dynamical calculations, which agrees with the present simple estimation. As a result of such strong shocks, electrons will be accelerated by the first-order Fermi process (Blandford & Eichler 1987).

Given the extinction coefficient $$\alpha_v,$$ the fraction of radiation absorbed by the dusty gas is $$\alpha = 1 - 10^{-0.4 A_{500}}.$$ We assume that the absorbed energies are converted into the kinetic luminosity of the winds $$L_{\text{kin}} = \eta_v \alpha \lambda L_{\text{Edd}} = 1.8 \times 10^{44} \eta_{v0.5} \alpha_{0.17} \lambda \xi_{0.1} a_{200}^2 \text{ ergs s}^{-1},$$ where $$\alpha_{0.17} = \alpha/0.17$$ for $$A_{v} = 0.2$$ and $$\eta_{v0.5} = \eta_v/0.5$$ is the processing efficiency. The total energy channelled into relativistic electrons is given by $$L_{\text{non-th}} = f_e L_{\text{kin}},$$ where $$f_e$$ is the acceleration efficiency converting the kinetic energy into the electrons. Although the detailed process of the acceleration is still insufficiently understood, it is generally taken as $$f_e = 0.05$$ (Blandford & Eichler 1987). We then have the nonthermal luminosity from the electrons

$$L_{\text{non-th}} = 0.9 \times 10^{-3} f_{e 0.05} \eta_{v0.5} \alpha_{0.17} \lambda \xi_{0.1} a_{200}^2 \text{ ergs s}^{-1},$$

(6)

where $$f_{e 0.05} = f_e/0.05.$$ The spectrum emitted from the electrons will be given in § 3.

2.2. Clumpy ISM

The physics of the infalling gas has been extensively discussed stemming from Fall & Rees (1985). The basic constraints on the medium are from the gravitational collapse and thermal conduction between the hot and cold phases (Fall & Rees 1985; Mo & Miralda-Escudé 1996). The typical temperature and density of the hot gas are of $$T_{h} = 10^6 \text{ K}$$ and $$n_{h} = 10^{-2} \text{ cm}^{-3}$$ in elliptical galaxies, respectively (Mathews & Brightenh 2003).

The lower limit of cold clouds is given by $$M_{\text{cold}} = 5.0 \times 10^{22} R_{21}^2 M_\odot$$ due to thermal conduction; otherwise they will be evaporated (Fall & Rees 1985), whereas the clouds will collapse into smaller ones if they are too massive (e.g., $$\sim 10^8 M_\odot$). We assume the clouds are spherical with radius $$R$$ and mass $$M = q M_{\text{cold}}$$ ($$q \geq 1).$$ A pressure balance $$n_t T_t = n_h T_h$$ holds between the clouds and their surroundings. The geometric covering factor can be defined as

$$C_R = \frac{\Delta \Omega}{4\pi} N_c,$$

(7)

where $$\Delta \Omega$$ is the solid angle of an individual cloud and $$N_c$$ is the total number of the cold clouds. This covering factor is the same with the probability that a quasar is a red one. Here we assume that all the clouds are identical with same size, shape, and physical conditions. For simplicity, we assume that the clouds are spherical. If the radius of the clouds is $$R,$$ and $$R, \ll R,$$ we have $$\Delta \Omega/4\pi = R^2/2 R^2,$$ where $$R$$ is the distance of the clouds to the galactic center. The number of the clouds is then estimated from equation (7) if the geometric covering factor is estimated from the percentage of red quasars. The individual cloud should not be too dense; otherwise the red quasars become type 2s. This constraint can be set up by the column density $$N_{10}$$ through the extinction coefficient $$A_v.$$ We then have the density and temperature

$$n_t = 8.4 q^{1/2} N_{21}^{3/2} \text{ cm}^{-3},$$

(8)

$$T_t = 1.2 \times 10^3 q^{1/2} n_{h-2} T_{h 6} \text{ K},$$

(9)

the radius $$R_t = 38.7 q^{1/2} N_{21}^{3/2} \text{ pc},$$ and the cloud number $$N_c = 1.3 \times 10^{16} C_{0.17}^{0.17} q^{-1} N_{21} R_{500} \text{pc},$$ where $$C_{0.17} = C_0/0.17,$$ $$T_{h 6} = T_h/10^5 \text{ K},$$ and $$n_{h-2} = n_h/10^{-2} \text{ cm}^{-3}.$$ Although we do not know the details of the parameter $$q,$$ we regard equations (8) and (9) as the typical values for $$n_t$$ and $$T_t$$ since they are not very sensitive to $$q.$$ The Mach number of the dusty winds in the clouds is

$$M = 9.3 \times 10^3 A_{500} (\lambda \xi_{0.1})^{1/2} T_5^{-1/2},$$

(10)

where $$T_t = T_h/10^3 \text{ K.}$$ The Mach number is stronger than the homogeneous ISM since the temperature is lower in the clouds. The shocked clouds produce relativistic electrons.

When a cloud is just on the line of an observer’s sight, the quasar appears as one red quasar. The transparent luminosity through the clouds is given by $$(1 - C_R) L_{\text{bol}}.$$ The total nonthermal luminosity from the quasar is $$L_{\text{non-th}} = (1 - C_R) L_{\text{bol}}.$$ The total nonthermal luminosity from the relativistic electrons is given by

$$L_{\text{non-th}} = f_e (1 - C_R) \xi_{0.1} \lambda L_{\text{Edd}},$$

(11)

Equation (1) is still valid for the clumpy ISM (Murray et al. 2005), but the shocks are produced mainly on the cold clouds.
3. ELECTRON ACCELERATION AND EMISSION

Some electrons will be energized to be relativistic through Fermi shock acceleration. The maximum energy of the relativistic electrons is determined by the energy gain and loss. Here we focus on the nonthermal radiation from the relativistic electron, rather than the detail of acceleration process. In this Letter, we assume that synchrotron radiation and inverse Compton scatter are the two main nonthermal radiation processes. Since the magnetic field is poorly understood in such a context, we assume an equipartition between the tangled magnetic field and the gas; then the energy density of the magnetic field \( U_B = 1.38 \times 10^{-12} (n, T_c) \) ergs cm\(^{-3}\) and \( B = 5.9 (n, T_c)^{1/2} \) \( \mu \)G, where \( (n, T_c) = n, T_c / 10^4 \) K \( \text{cm}^{-3}\). There are three sources of the seed photons of Compton scattering: (1) from the nucleus of quasars, (2) from the reprocessed photons by the clouds, (3) from synchrotron photons, and (4) from the host galaxies. However, light from hosts can be neglected for quasars bright enough. The second could be neglected since they are only \( \sim 10\% \) of the first source (if the optical depth \( \tau \approx A_v \) for \( A_v = 0.1 \), but may be important for the very red quasars or reddened quasars). The energy loss is mainly due to synchrotron radiation and inverse Compton scattering of the seed photons from the quasar’s nucleus.

The energy density of quasar’s radiation is given by \( U_{\text{qso}} = 7.7 \times 10^{-11} L_{14} R_6 B_6 \) ergs cm\(^{-3}\) at \( R \) from the center, where \( R_6 \text{ kpc} = R / 6 \) kpc and \( L_{14} = L / 10^{46} \) ergs s\(^{-1}\). We find that \( U_{\text{qso}} \gg U_B \), indicating that the energy loss is mainly due to external inverse Compton scattering provided by the red quasars. The synchrotron self-Compton scattering can be neglected in such a context. For simplicity, we assume the quasar spectrum is characterized by a blackbody with a temperature of \( 10^4 \) K from the standard accretion disk (Inoue & Takahara 1996). The timescale of energy loss due to the inverse Compton scattering is \( t_{\text{loss}} = 3.0 \times 10^7 \tau^{-1} U^{-1} \) s, where \( U \approx U_{\text{qso}} \), whereas the acceleration timescale reads \( t_{\text{acc}} = R_c c / v_{\text{sh}} \) (Blandford & Eichler 1987), where \( R_c \) is the Larmor radius and \( v_{\text{sh}} \approx v_{\text{max}} \approx 10^8 \) cm s\(^{-1}\) is the shock velocity. The maximum Lorentz factor of the electrons is given by \( \gamma_{\text{max}} = t_{\text{acc}} / t_{\text{loss}} \),

\[
\gamma_{\text{max}} = 7.7 \times 10^6 v_{\text{sh},8} U_{-10}^{-1/2} B_{-6}^{1/2},
\]

where \( U_{-10} = U / 10^{-10} \) ergs cm\(^{-3}\), \( v_{\text{sh},8} = v_{\text{sh}} / 10^8 \) cm s\(^{-1}\), and \( B_{-6} = B / 10^{-6} \) G. The synchrotron radiation gets a peak at

\[
\nu_{\text{syn}} = 4.5 \times 10^{13} B_{-6} \gamma_{\text{max}}^2 \text{ Hz},
\]

where \( \gamma_{\text{max}} = \gamma_{\text{max}} / 10^7 \). The peak frequency due to inverse Compton scattering is

\[
\nu_{\text{IC}} \approx \gamma^2 \nu_{\text{disk}} = 3.6 \times 10^{27} (\gamma / \gamma_{\text{max}})^2 T_4 \text{ Hz},
\]

where \( \nu_{\text{disk}} = 3kT_{\text{disk}} / h \), \( h \) is the Planck constant, and \( T_{\text{disk}} = 10^4 T_4 \) K is the maximum temperature in Shakura-Sunyaev disk for quasars. We assume a simple power law of the electrons as \( N(\gamma) = N_0 \gamma^{-\alpha} \) in a range of \( \gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{max}} \) via the first-order Fermi acceleration, where \( \gamma_{\text{min}} \) is the minimum Lorentz factor. We treat \( \gamma_{\text{min}} \) as a free parameter in this Letter. \( N_0 \) is determined by equation (6) or (11). For a red quasar containing a black hole with \( M_\bullet = 10^5 M_\odot \), we plot the multiwavelength continuum of the fuzz for three different values of \( n \) in Figure 1. It should be noted that the difference between \( \gamma_{\text{max}} \) and the spectrum in Figure 1 is due to the inclusion of the Klein-Nishina effects in the latter.

Some uncertainties of the proposed model should be noted, which are most likely because of the dependence of the factor \( A \) on the thermal state of the medium as shown in Fabian et al. (2006). Here we use the maximum \( A \). The \( \gamma_{\text{max}} \), depending on the shock velocity, could be lowered when \( A \) decreases, leading to the synchrotron peak shifts to long wavelength as well as the inverse Compton peak. We use a magnetic field in an equipartition with the thermal energy of medium, but it cannot deviate from the equipartition too much.
4. DETECTING THE FUZZ

The isothermal sphere under the galactic potential gives the density $\rho(R) = f_1 \sigma^2/2 \pi GR^2$; we have the column density of the gas exterior to $R_{\text{exp}}$, $N_\text{H} = f_1 \sigma^2/2 \pi GmR = 3.0 \times 10^{21} f_1 \sigma^2/2 \pi Gm R_{\text{exp}}$ cm$^{-2}$, where $f_1 = 0.1 f_{\text{H}_{\text{O}}} s$ is the gas fraction (Fabian et al. 2006). This leads to an extinction coefficient $A_v = 0.2 Q_{\text{p}} N_\text{H}$, appearing as a red quasar, where $N_\text{H} = N_{\text{H}}/10^{21}$ cm$^{-2}$ and $Q_{\text{p}} = Q/500$ is the gas-to-dust ratio (Gorenstein 1975). We note that the sweeping timescale of the radiative-driven winds is $\tau_\text{w} = R/V(R) = 2.2 \times 10^4 R_{\text{exp}} (V/\text{max})^{-1}$ yr. The lifetime of quasars $\tau_\text{qH}$ is about the Salpeter time $\tau_{\text{S}} = 4.5 \times 10^7 \eta^{-0.1}$ yr ($\eta = \eta(0.1$ is the radiative efficiency); we have the percentage of red quasars at a level of $\tau/\tau_\text{qH} \approx 5.0\%$. This roughly agrees with the results from the SDSS (Richards et al. 2003).

The targets for searching the fuzz can be found from those low-redshift red quasars from the FIRST-2MASS, Spitzer, and Sloan samples. Table 1 gives the future detections of the fuzz through multiwavelength telescopes. The predicted fuzz has a level of $10^{20} - 10^{21}$ erg s$^{-1}$, which would easily be detected by radio telescopes, IR-band telescopes are obviously capable of imaging the fuzz; in particular, ALMA and JWST will be able to detect the fuzz at $z > 0.2$ in the future. The fuzz could only be marginally detected by the existing HESS and VERITAS, but it is worth making an attempt. GLAST is anticipated to explore the fuzz more feasibly. We have to note that TeV emission from the fuzz could be diluted via $\gamma-\gamma$ interaction by the cosmic IR background photons beyond redshift $z = 0.2$. So it is not expected that $\gamma$-ray telescopes will detect the TeV emission from fuzz for red quasars with $z > 0.2$. If the episodic activity of supermassive black holes is really caused by a series of mergers of galaxies (Marconi et al. 2004; Di Matteo et al. 2005; Wang et al. 2006, 2008), there is no doubt that the detection of the fuzz will provide the most powerful diagnostic to the evolutionary chains of galaxies and quasars from details of radiative feedback.

Finally, it should be mentioned that X-ray emission from fuzz is extremely faint unless the maximum Lorentz factor is lowered by a factor of 10. This could be plausible if the factor $A$ decreases by a factor of 10. In such a context, the fuzz is able to produce hard X-rays detected by NuSTAR (Nuclear Spectroscopic Telescope Array) and HXMT (Hard X-Ray Modulation Telescope).

5. CONCLUSION AND DISCUSSION

In this Letter, we show that enhanced radiation pressure inevitably leads to strong shocks in the dusty gas of both homogeneous and clumpy ISM. The first Fermi shock acceleration results in production of relativistic electrons in the shocked ISM, which produces nonthermal emission via synchrotron radiation and inverse Compton scattering, displaying multiwavelength fuzz from radio, infrared, and $\gamma$-ray bands. The current radio telescopes, MIPS, HESS, and VERITAS, are capable of detecting the fuzz. The multiwavelength image of the fuzz provides an interesting and new clue for understanding the interaction between quasars and their environments.

The predicted $\gamma$-ray emission from fuzz could make a significant contribution to cosmic $\gamma$-ray background if all quasars have to undergo such a red phase during their cosmic evolution. We will study this problem in the future.

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| Instruments | $z = 0.01, \theta \approx 30^\circ$ | $z = 0.2, \theta \approx 2^\circ$ |
|-------------|-----------------|-----------------|
| ALMA        | 47.4            | 16.8            |
| MIPS        | 3.0             | 1.0             |
| JWST        | 0.4             | 0.14            |
| GLAST       | 150             | Yes             |
| HESS (I)    | 0.03            | Marginal        |
| VERITAS     | 0.03            | Marginal        |
| HESS (II)   | 0.03            | Yes             |

Notes.—Here $\theta$ is the angular radius (in arcseconds) at $z$. Col. (1): Instrument name. Col. (2): Flux (in mJy). Col. (3): Brightness ($\mu$Jy arcsec$^{-2}$) for ALMA, MIPS, and JWST, but in $10^{-6}$ photons s$^{-1}$ cm$^{-2}$ for $\gamma$-ray detectors.Cols. (5) and (6): Same as cols. (2) and (3), but in $\mu$Jy and $\mu$Jy arcsec$^{-2}$ for $z = 0.2$. We assume the cosmological constants $H_0 = 71$ Mpc km$^{-1}$ s$^{-1}$, $\Omega_m = 0.27$, and $\Omega = 0.73$. ALMA: Atacama Large Millimeter/Submillimeter Array, spatial resolution $\Delta\theta = 0.005''$ at $\nu = 900$ GHz. MIPS: Multiband Imaging Photometer for Spitzer, $\Delta\theta = 3''$, working at 24, 70, and 160 $\mu$m. JWST: James Webb Space Telescope, here for NIR camera at 5 $\mu$m. GLAST: Gamma-ray Large Area Space Telescope (100 MeV), sensitivity $\sim 10^{-4}$ photons s$^{-1}$ cm$^{-2}$. HESS: High Energy Spectroscopic System (100 GeV), sensitivity $\sim 10^{-10}$ (phase I) and $10^{-9}$ photons s$^{-1}$ cm$^{-2}$ (phase II). VERITAS: Very Energetic Radiation Imaging Telescope Array System.

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