Observational Appearance of Relativistic, Spherically Symmetric Massive Winds

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Abstract

The photon mean free path in a relativistically moving medium becomes long in the downstream direction, while short in the upstream direction. As a result, the observed optical depth, $\tau$, becomes small in the downstream direction while large in the upstream direction. Therefore, if a relativistic spherical wind blows off, the optical depth depends strongly on its speed and the angle between the velocity and the line-of-sight. Abramowicz, Novikov, and Paczyński (1991, ApJ, 369, 175) examined such a relativistic wind, and found that the shape of the photosphere at $\tau = 1$ appears to be convex in the nonrelativistic case, but concave for relativistic velocities. We further calculated the temperature distribution and luminosity of the photosphere both in the comoving and inertial frames. We found that the limb-darkening effect would be strongly modified in the relativistic regime. We also found that the luminosities of the photosphere become large as the wind speed increases due to relativistic effects. In addition, the luminosity in the inertial frame is higher than that in the comoving frame. These results suggest that the observed temperature and brightness in luminous objects may be overestimated when there are strong relativistic winds.

Key words: accretion, accretion disks — black hole physics — radiative transfer — relativity — stars: winds

1. Introduction

Recent observations have revealed the existence of highly luminous objects, such as ultraluminous X-ray sources (ULXs) in nearby galaxies, narrow line Seyfert 1 galaxies (NLS1s), and bright PG quasars. Bright objects are paid to attention because outflow is observed in those objects. The bright quasar PG 1211+143 seems to have a relatively high-velocity outflow ($v \sim 0.1c$) based on broad absorption line features observed by XMM-Newton (Pounds et al. 2003a). The bright quasar PG 0844+349 also shows several absorption features in its X-ray spectrum, and the outflow velocity is on the order of $\sim 0.2c$ (Pounds et al. 2003b). Moreover, PKS 1549–79 is a luminous quasar-like active galactic nucleus, which contains relatively narrow permitted lines, highly blueshifted [O III] lines, which are well observed in NLS1s. Since the Very Large Telescope (VLT) observation of PKS 1549–79 shows outflow-like images, there is evidence that high mass accretion and warm outflow coexist in this object (Holt et al. 2006).

Optical observations of broad absorption line (BAL) quasars have also suggested the existence of not-collimated, relativistic outflows. The typical wind velocity estimated by their line width is about 10000–30000 km s$^{-1}$. The high column density of $N_{\text{H}} \sim 10^{23}–24$ cm$^{-2}$ suggests that large amounts of gas are moving around the central region of BAL quasars.

King and Pounds (2003) recently suggested that highly optically thick, relativistic winds — “black hole winds” — blow off from the central part of accretion disks, and produce a large luminosity, which may be observed in PG 1211+143 and ULXs. If the mass-outflow rate of the wind increases, the optical depth of the wind exceeds unity, and eventually such a massive wind may form a “photosphere”, like the sun. Because the location of the photosphere depends on the wind velocity and mass-outflow rate, we may observe the light from an outflow, rather than that from an accretion disk. Therefore, determining the location of the photosphere is quite important from an observational viewpoint.

Spherically symmetric, relativistic winds have been investigated by several researchers (e.g., Castor 1972; Ruggles & Bath 1979; Mihalas 1980; Quinn & Paczyński 1985; Turolla et al. 1986; Paczyński 1990; Akizuki & Fukue 2007), and their models have been applied to neutron-star winds and gamma-ray burst (GRB). However, in these studies they focused on the dynamics of the relativistic outflow, and did not concentrate on the observational implications. Abramowicz, Novikov, and Paczyński (1991) first examined the observational appearance of relativistic, spherical winds, using a simple model at a constant speed. They found that the shape of the photosphere appears to be convex in the non-relativistic case, but concave in a relativistic regime.

Abramowicz, Novikov, and Paczyński (1991) only considered the apparent shape of the photosphere of relativistic spherical winds. Thus, in this paper, we further examine the relativistic spherical winds, while focusing our attention on the observational appearance, such as the observed temperature distribution and the emergent luminosity, and give observational implications to several PG quasars and ULXs.

In section 2, we briefly introduce the present wind model, and describe the calculation method. Section 3 demonstrates the results, and discussions and applications are presented in section 4. The final section is devoted to concluding remarks.
2. Model and Calculation Method

In this section we describe the present wind model and the calculation method.

2.1. Wind Model

Our present model is based on a model by Abramowicz, Novikov, and Paczyński (1991). We briefly summarize the simple model at a constant velocity.

We assume that a spherically symmetric, relativistic wind blows off from a central object. As a central object, we assume a nonrotating black hole (Schwarzschild black hole), and the Schwarzschild radius is defined by \( r_s = 2GM/c^2 \), where \( G \), \( M \), and \( c \) represent the gravitational constant, black hole mass, and the speed of light, respectively. We use spherical coordinates \((R, \theta, \varphi)\) and cylindrical coordinates \((r, \varphi, z)\), whose \( z\)-axis is along the line-of-sight (see figure 1).

From the continuity equation, the rest mass density, \( \rho_0 \), measured in the comoving frame, varies as

\[
\rho_0 = \left( \frac{\dot{M}}{4\pi v\gamma} \right) R^{-2},
\]

where \( \dot{M} \) is the mass-loss rate, \( R = \sqrt{r^2 + z^2} \) the distance from the central object, and \( \gamma \) the Lorentz factor of the wind, expressed as

\[
\gamma \equiv (1 - \beta^2)^{-1/2}, \quad \beta \equiv \frac{v}{c}.
\]

Quantities with subscript “0” refer to physical quantities measured in the comoving frame.

In the present simple model, the mass-loss rate, \( \dot{M} \), and wind velocity, \( v \), are assumed to be constant.

2.2. Photosphere of the Wind

We define an “apparent photosphere” of the wind as the surface, where the optical depth, \( \tau \), measured from an observer, becomes unity. A schematic picture of our present calculation is presented in figure 1.

Let us consider a small distance \( ds \) along the light path. Due to the relativistic effect, the mean free path of photons in the fixed frame, \( \ell \), is related to that in the comoving frame, \( \ell_0 \), by

\[
\ell = \frac{1}{\gamma (1 - \beta \cos \theta)} \ell_0,
\]

where \( \theta \) is the viewing angle measured from the \( z\)-axis. Then, the optical depth in the fixed frame is given by

\[
d\tau = \gamma (1 - \beta \cos \theta) \kappa \rho_0 ds,
\]

where the opacity, \( \kappa \), is assumed to be electron scattering (Abramowicz et al. 1991). Thus, the optical depth strongly depends on the viewing angle, \( \theta \), as well as the flow speed, \( v \). It is obvious that the optical depth is smallest in the downstream direction at \( \theta = 0 \), where the photons move in the same direction with the fluid, while it becomes largest in the upstream direction at \( \theta = \pi \), where the photons move in the opposite direction to the fluid.

From equation (4), the integrated optical depth, \( \tau_{ph} \), from an observer at infinity is calculated as

\[
\tau_{ph} = \int_{z_{ph}}^{\infty} \gamma (1 - \beta \cos \theta) \kappa \rho_0 ds = 1,
\]

where \( z_{ph} \) is the location of the apparent photosphere from the equatorial plane. Abramowicz, Novikov, and Paczyński (1991) showed that the photosphere of a highly relativistic wind is much closer to the source, roughly by a factor of \( \gamma^2 \). Although the nonrelativistic and moderately relativistic winds have convex photospheres, the photospheres of the relativistic wind becomes concave for \( \beta > 2/3 \) (see figure 2).

2.3. Temperature Distribution and Luminosity

In the present model, we assume that the spherical wind expands adiabatically. Then, the temperature, \( T_0 \), of the wind gas in the comoving frame varies as \( T_0 \propto \rho_0^{\Gamma - 1} \propto R^{1/3} \propto R^{-2/3} \), where \( \Gamma \) is the ratio of specific heats, and is set to be 4/3 for a radiation pressure dominant regime. Hence, the temperature distribution in the comoving frame is

\[
\frac{T_0}{T_c} = \left( \frac{R}{R_c} \right)^{-2/3},
\]

where \( T_c \) is the central temperature at \( R = R_c \).

Furthermore, the observed temperature \( T \) in the observer’s frame is expressed by

\[
T = \frac{1}{1 + z} T_0 = \frac{1}{\gamma (1 - \beta \cos \theta)} T_0,
\]
where $z$ is the redshift via longitudinal and transverse Doppler effects. Using this observed temperature, we can obtain the observed luminosity by

$$L = \int_{r_{\text{out}}}^{r_{\text{in}}} 2\pi r dr \times F dr,$$

where $F$ is the observed flux, $F = \sigma T^4$ when we assume the blackbody radiation, $\sigma$ being the Stefan–Boltzmann constant. This integration has been performed at $z \rightarrow \infty$ in the observer’s frame, and thus the effect of curvature of the photosphere is automatically included.

3. Results

We determined the photosphere for various $\beta$ via equation (5), and obtained the temperature and luminosity on the surface of the photosphere in the comoving and inertial frames. In the present calculation, we bear in mind the case for active galactic nuclei, although the present results are also important for black-hole binaries. Hence, the black hole mass and temperature at the central region are fixed as $M = 10^7 M_\odot$ and $T_c = 10^7 K$, respectively. The input parameters are then the velocity, $\beta$, and the normalized mass-loss rate, $\dot{m}$, of the wind, where the mass-loss rate is normalized by the critical rate, $\dot{m} = M/M_{\text{crit}} = M/(L_E/c^2)$, $L_E$ being the Eddington luminosity.

3.1. Location of the Photosphere

Figure 2 shows the location of the apparent photosphere seen by the observer at infinity in the $z$-direction for various wind velocities. In the low-speed regime, the photosphere near the $z$ axis is close to the center, while the photosphere far away from the $z$ axis is far from the center. This is the usual limb-darkening effect of the spherically expanding wind.

In the high-speed regime, on the other hand, the shape of the apparent photosphere changes, because the optical depth depends on the angle $\theta$ and the wind velocity, $v$. In particular, when the wind blows off at a highly relativistic speed ($\beta \gtrsim 0.8$), the photosphere looks like a concave shape.

Our results are consistent with the analytical results by Abramowicz, Novikov, and Paczyński (1991), but we note that our coordinates are expressed in units of the Schwarzschild radius, $r_g$.

3.2. Temperature Distribution

In figure 3 we show the temperature distributions in the comoving and inertial frames, respectively, viewed by an observer at infinity in the direction of the $z$-axis. In general, the wind photosphere looks brightest at the central part, and the surroundings are gradually dim with increasing radius. This is due to the limb-darkening effect seen in the usual spherical wind.

In the relativistic wind considered here, however, this limb-darkening effect is remarkably enhanced. This is due in part to the relativistic Doppler and aberration effects, and due in part to the fact that the observed photosphere shrinks as the velocity increases, and we can see deep inside the wind.

Comparing the temperature distributions in the comoving and inertial frames, we can see that the central temperature in the inertial frame is higher than that in the comoving frame. This is just the relativistic Doppler and aberration effects. That is, the observed temperature increases as $\theta$ approaches zero because of the longitudinal Doppler effect (highly beamed emission). This effect also becomes remarkable as the velocity increases.

3.3. Apparent Luminosity

In figure 4, we show the luminosities of the relativistic winds as a function of the wind velocity, $\beta$, for several mass-loss rates, $\dot{m}$. The solid curves represent the observed luminosity in the inertial frame, and the dashed curves show the comoving luminosity.

As can be seen in figure 4, the wind luminosity increases as the velocity increases, while it decreases as the mass-loss rate increases. In addition, the luminosity observed in the inertial frame is higher than that observed in the comoving frame.

In the present calculation, the location of the photosphere strongly depends on the density of the wind. Namely, as the mass-loss rate increases, the wind density increases, and the location of the photosphere expands to the outer region. Since the temperature of the wind in the outer region is lower than that in the inner region, the luminosity decreases as the mass-loss rate increases.

Moreover, by the effect of Doppler beaming, the observed luminosity increases as the velocity increases. It is emphasized that the comoving luminosity is enhanced by about 130% for $\beta = 0.2$, but the amplification is about one order for $\beta = 0.9$. These facts suggest that there is a possibility of an overestimation of the observed luminosities for relativistic outflow objects.

4. Discussions

4.1. Observational Importance of the Apparent Photosphere

The observed shape of the photosphere is asymmetric in spite of spherically symmetric winds. This is due to the limb-darkening effect. This nature does not depend on the observer’s direction. Due to the optical depth effect, we could see deeper inside the wind, as the velocity increases. In
Fig. 3. Temperature distribution at the apparent photosphere viewed by an observer at infinity in the z-direction. The left and right panels show the temperatures in the comoving and fixed (observer’s) frames, respectively. The wind velocity, $\beta$, is varied as 0.2, 0.4, 0.6, and 0.8 from top to bottom in both panels.
radiation-pressure driven wind is difficult to be accelerated up to a mildly relativistic speed (e.g., Proga 2003; Ohsuga et al. 2005). Unfortunately, a sample number of PG quasars is insufficient for a statistical argument. Moreover, absorption lines observed in PG 0844+349 are highly suspectable because reanalysis of the same data by other group did not confirm the earlier results (Brinkman et al. 2006). Thus, we hope that further reliable detections of the broad absorption lines in BAL quasars will confirm the existence of mildly relativistic outflows.

5. Concluding Remarks

In this paper, we examined the appearance of relativistic, spherically symmetric wind from an observational point of view. As for the shape of the apparent photosphere of massive winds, we confirmed the results of Abramowicz, Novikov, and Paczyński (1991). We further calculated the temperature distribution and luminosity of the photosphere both in the comoving and inertial frames. We found that the limb-darkening effect would be strongly modified in the relativistic regime. We also found that the luminosities of the photosphere become large as the wind speed increases due to relativistic effects. In addition, the luminosity in the inertial frame is higher than that in the comoving frame. In particular, the luminosity in the observer’s frame is one order of magnitude higher than that in the comoving frame for highly relativistic regimes. We suggest that if the observed luminosity is used to evaluate the black hole mass, then the derived black hole mass will be overestimated.

In order to compare with observational data, we need more strict treatments of a wind model, e.g., the effect of general relativity, radiative energy loss in the wind, Compton processes, acceration by radiation pressure, etc. However, the aim of this paper is to show the possibility of forming a photosphere. Here, we explicitly show the formation of a photosphere in an optically thick wind using a simple spherical wind model.

Strictly speaking, the observed temperature should be evaluated from the temperature on the surface, where the effective optical depth equals to unity, $\tau_{\text{eff}} = (\tau_{\text{ff}} \tau_{\text{es}})^{1/2} = [\tau_{\text{ff}}(\tau_{\text{ff}} + \tau_{\text{es}})]^{1/2} = 1$, $\tau_{\text{ff}}$ and $\tau_{\text{es}}$ being the free-free and electron-scattering opacities, respectively. In a high-temperature plasma, the effective optical depth is often smaller that the total optical depth, and the gas becomes scattering dominant. In such a scattering-dominated plasma, the emergent spectrum is not a simple blackbody, but a modified blackbody (e.g., Rybicki & Lightman 1979). In addition, we have used the Thomson cross section for electron scattering. When the center-of-mass energy of scattering becomes relativistic ($h\nu \sim 100$ keV), we should use the Klein–Nishina cross section, which reduces the effective cross section. In such a highly relativistic regime, a wind will be much more transparent. These effects are also left as future problems.

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![Fig. 4. Luminosity of the relativistic wind as a function of the wind velocity for several mass-loss rates. The solid curves represent the observed luminosity in the inertial frame, and the dashed curves show the comoving luminosity. The mass-loss rates, $\dot{m}$, are 10, 100, 1000, and 10000 from top to bottom.](https://academic.oup.com/pasj/article-abstract/59/5/1043/1429594)
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