Flaring up of the compact cloud G2 during the close encounter with Sgr A*

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Abstract

A compact gas cloud G2 is predicted to reach the pericenter of its orbit around the supermassive black hole (SMBH) of our Galaxy, Sagittarius A*. This event will give us a rare opportunity to observe the interaction between the SMBH and the gas around it. We report on the result of a fully three-dimensional simulation of the evolution of G2 during the first pericenter passage. The strong tidal force from the SMBH stretches the cloud along its orbit, and strongly compresses it in the vertical direction, resulting in its heating up and flaring up. The bolometric luminosity will reach a maximum of \( \sim 100 L_\odot \). This flare should be easily observed in the near-IR.

Key words: Galaxy: center — Galaxy: nucleus — methods: numerical

1 Introduction

At present the activity of Sagittarius A* (Sgr A*) seems to be in the low state, with an X-ray luminosity of \( 10^{33} \) erg s\(^{-1}\) (Baganoff et al. 2003). There is evidence of past activities (Sunyaev et al. 1993; Koyama et al. 1996; Dobler et al. 2010; Su et al. 2010) where the luminosity reached as high as \( 10^{40} \) erg s\(^{-1}\). Recently, rapid flaring from Sgr A* has been observed at various wavelengths (Tsuboi et al. 1999; Baganoff et al. 2001; Genzel et al. 2003; Miyazaki et al. 2004). Thus it is quite important to understand how these large variations in luminosity took place. One possibility is the intermittent supply of gas in the form of high-density clouds.

The compact cloud G2 (Gillessen et al. 2012) might offer us the first opportunity to study such an interaction between a gas cloud and a supermassive black hole (SMBH). While the formation mechanism of the cloud is under debate (Burkert et al. 2012; Gillessen et al. 2012; Miralda-Escudé 2012; Murray-Clay & Loeb 2012; Meyer & Meyer-Hofmeister 2012; Scoville & Burkert 2013), we
know that the orbit of G2, determined from observations since 2004, is highly eccentric, and G2 will reach the pericenter of its orbit in midyear 2013 (2013.51 ± 0.04), with a pericenter distance of only 270 au (Gillessen et al. 2012). Gillessen et al. (2013a) reported that updates of the pericentric distance and the time of pericenter passage are 190 au and 2013 September (2013.69 ± 0.04), respectively. Phifer et al. (2013) reported different values of 130 au and 2014 March (2014.21 ± 0.14). In Gillessen et al. (2013b), these are now 210 au and 2014 March (2014.25 ± 0.06).

Schartmann et al. (2012) studied the evolution of G2 using a high-resolution adaptive mesh refinement calculation in two dimensions. In their calculation, the cloud loses kinetic energy during the pericenter passage due to the ram pressure from the hot atmosphere around the SMBH, and gas accretion to the SMBH starts early in 2013, continuing for several decades with a nearly constant accretion rate.

However, it is not clear whether or not the two-dimensional calculation is appropriate. The cloud should experience strong compression in the direction perpendicular to the orbital plane, due to the tidal force from the SMBH, resulting in a very thin structure. Because of this structure change, the ram pressure might become ineffective, unlike the two-dimensional simulations. In addition, this compression energy is emitted immediately via radiation. It is therefore expected that the luminosity of the cloud will increase during the pericenter passage. Since the tidal force in the vertical direction is proportional to the distance from the orbital plane, the cloud will contract uniformly. There is no shock during this contraction, as long as the cloud maintains a finite thickness. Anninos et al. (2012) carried out the three-dimensional mesh simulations, but they neglected effects of radiative cooling and therefore did not notice this brightening.

In order to study these effects, we performed fully three-dimensional simulations, in which the compressional heating and radiative cooling of the cloud are consistently taken into account.

2 Method

We solved the evolution of a system consisting of Sgr A*, hot ambient gas, and the cloud by N-body/smoothed-particle hydrodynamics (SPH) simulations. Here, we adopted the compact cloud scenario given in Burkert et al. (2012).

We modeled Sgr A* as a sink particle (Bate & Burkert 1997) with a mass of $4.31 \times 10^6 M_\odot$ (Gillessen et al. 2009). This sink particle can absorb nearby gas particles. The sink radius is 30 au, which is 350 times larger than the real horizon scale of the SMBH, 0.085 au, and is 10 times smaller than the pericentric distance. When a gas particle is absorbed by the sink particle, the gas particle is removed and its mass is added to that of the sink particle. We did not consider the emission from the absorbed gas since observations suggest that accretion flow around Sgr A* is expressed by radiatively inefficient accretion flow (RIAF: Ichimaru 1977; Narayan & Yi 1994).

A diffuse and hot X-ray-emitting gas around Sgr A* (Yuan et al. 2003; Xu et al. 2006) was modeled by Yuan’s RIAF model (Yuan et al. 2003), that previous studies of G2 (Gillessen et al. 2012; Burkert et al. 2012, Schartmann et al. 2012) followed. The density and temperature profiles are given by

$$\rho_{\text{hot}}(r) = 1.7 \times 10^{-21} f_{\text{hot}} \left(1.0 \times 10^{16} \text{ cm} \right) g \text{ cm}^{-3},$$

$$T_{\text{hot}}(r) = 2.1 \times 10^8 \left(1.0 \times 10^{16} \text{ cm} \right) K,$$

where $r$ is the distance from Sgr A* and $f_{\text{hot}}$ is the scaling parameter of gas density. We changed $f_{\text{hot}}$ from 1.0 (Run 1) through 0.1 (Run 2) to 0 (Run 3) in order to investigate the effect of the hot gas on the evolution of G2. The rotation and inhomogeneity of the hot gas at the initial state were neglected, whereas dynamical evolution was allowed. Although this profile is convectively unstable (Schartmann et al. 2012), we did not try to prevent the growth of convection. In our model, we allowed the radiative cooling of the hot gas, resulting in an accretion rate consistent with the value suggested by the observation. Because of this accretion flow, the growth of convection was effectively suppressed.

The cloud, G2, was modeled as a spherical gas cloud in units of Earth’s mass and a uniform density distribution. The initial radius of the cloud is 125 au and the initial temperature of the gas is 10 $^\circ$K. The orbit of the cloud is that of Gillessen et al. (2012), where the pericentric distance is 270 au and the time of pericenter passage is 2013.5. We adopted AD 1995 as the starting epoch of the simulations and solved the evolution of the cloud for 38 yr. This cloud was in hydrostatic equilibrium with the ambient gas in AD 1995, $r_{1995} \approx 5100$ au; the pressure ratio of the cloud to the hot ambient gas was $1.1/f_{\text{hot}}$. If the cloud forms at the apocenter, it should have quite an elongated structure, which is inconsistent with the observation (Burkert et al. 2012).

The particle number, mass, and spatial resolution of the cloud, hot ambient gas, and SMBH are summarized in table 1.

We used ASURA, a parallel N-body/SPH simulation code, for these simulations (Saitoh et al. 2008, 2009). Gravity was solved by the “tree with GRAPE” method (Makino 1991b). A symmetrized potential was used in order to
accelerate the gravity calculation with a tree having the individual softening length (Saitoh & Makino 2012). In this study, we adopted the density-independent SPH (Saitoh & Makino 2013) in which the pressure, or the energy density, is evaluated first, and other quantities are evaluated by using the pressure. This formulation can successfully operate hydrodynamical instabilities. This ability would be important since, according to Burkert et al. (2012), hydrodynamical instabilities might play important roles in the cloud evolution, in particular at the pericenter. We used the second-order symplectic integrator, the leapfrog method, and the individual time-step method (McMillan 1986; Makino 1991a). The FAST method (Saitoh & Makino 2010) and the time-step limiter (Saitoh & Makino 2009) were also used.

We adopted the Monaghan-type artificial viscosity term (Monaghan 1997) to handle the shock. To avoid penetration of particles in the vertical direction at the pericenter passage, we adopted a rather large value of the viscosity parameter, $\alpha = 6$. The radiative cooling and the photoelectric heating due to the far-UV field were taken into account in the form of a cooling/heating function (Wada et al. 2009; Wolfire et al. 1995), and an optically thin approximation was used. With this function, the far-UV heating is modeled through the heating rate $G_0$ (see appendix B in Wada et al. 2009). The covered range of $G_0$ is $0-10^{4}$, which corresponds to $0-6000$ times that of the solar neighborhood. On the other hand, if we assume that the far-UV heating is proportional to the local stellar density, it is $10^7$ times that of the solar neighborhood. The stellar density at the galactic center is $\sim 10^6 \, M_\odot \, pc^{-3}$ (Genzel et al. 1996; Haller et al. 1996), and that at the solar neighborhood is $\sim 0.05 \, M_\odot \, pc^{-3}$ (Creze et al. 1998; Holmberg & Flynn 2000). Therefore, we could not give far-UV heating sufficient strength. We discuss what is expected when we used $G_0 \sim 10^7 \, M_\odot$ for gas, since the metallicity at the galactic center region is $1.5-3 \, Z_\odot$ (Genzel et al. 2010).

Since the radiative cooling is very strong, the temperature of the gas cloud is always less than $10^4 \, K$. This is the reason why previous studies excluded radiative cooling and often assumed adiabatic or isothermal equations of state (Burkert et al. 2012; Schartmann et al. 2012; Anninos et al. 2012). However, as we show in this paper, it is quite important for predicting the evolution of luminosity to include the effect of radiative cooling.

### 3 Results

Figure 1 shows the evolution of the three-dimensional structure of the cloud from $AD$ 2006.26 to 2013.46. For this model we used $f_{\text{hot}} = 1$, which is similar to that used in the previous two-dimensional calculations (Burkert et al. 2012; Schartmann et al. 2012). At $AD$ 2006, the simulated G2 was nearly spherical, since the effect of the tidal force is inefficient. The destruction effect due to hydrodynamical instabilities is also inefficient since the time scale of instabilities is sufficiently long, $\sim 10 \, yr$ (Gillessen et al. 2012). By $AD$ 2012.02, it is stretched in the orbital plane and compressed in the vertical direction. This stretch has already been observed (Gillessen et al. 2012). When the cloud passes the pericenter, its thickness reaches a minimum. Due to this strong vertical compression, the gas density increases by more than two orders of magnitude.

In the last panels (panels d and d'), we can see the “bridge” between the central SMBH and the head of the cloud. This bridge indicates that there is a flow of gas from the head of the cloud to the SMBH. However, the amount of gas in this bridge, and the resulting accretion rate to the SMBH, are small.

Figure 2 shows the history of the accretion rates. We show the results of two out of the three runs. For the first run, we used the same cloud model as in Burkert et al. (2012) and Schartmann et al. (2012), except that we solved the dynamical evolution of the hot ambient gas. Whether or not such a high-density, high-temperature atmosphere actually exists near the SMBH is an open question. In order to measure the importance of the assumption on the hot atmosphere, we performed two additional simulations. In the second run, we reduced the gas density by a factor of 10 (red dashed curve in figure 2), and in the third run we eliminated the atmosphere altogether.

In the case of the standard run, the accretion rate of the gas from the cloud reaches the peak value of $\sim 10^{-7} \, M_\odot \, yr^{-1}$ at $AD$ 2014, and then decreases exponentially. The accretion rate at $AD$ 2030 is one order of magnitude smaller than the peak value.

These behaviors are quite different from those in the two-dimensional calculations (Schartmann et al. 2012), in which the accretion rate is nearly constant due to the strong ram...
Fig. 1. Time evolution of the structure of G2 during the period from AD 2006.26 to AD 2013.46, tagged with a to d and a’ to d’. The density distributions in the xy-planes (a to d) and the selected planes (a’ to d’) are shown. Here, the xy-plane corresponds to the orbital plane of G2. The thin solid lines in the panels for the xy-plane show the location of the plane for which the density distributions are shown in the corresponding panels for the selected planes. The top-right two panels show the distribution at AD 2013.46. Panel e depicts part of the orbit of G2 (solid curve) and the positions of the xy-plane in the four epochs (red squares). The blue hexagon indicates the position of the cloud at AD 1995.5. The plotted region is $-7000 \text{ au} < x < 2000 \text{ au}$ and $-800 \text{ au} < y < 2200 \text{ au}$. (Color online)

Fig. 2. Time evolution of the accretion rate of the gas to the SMBH. The black and red curves are the results of simulations with the standard high-density hot atmosphere (Run1) and with a low-density atmosphere (Run2), respectively. The thick curves show the accretion rates of the cloud gas, and the thin curves show those of the halo gas. The vertical line denotes the epoch of 2013 January 1. When we excluded the hot ambient, there was no accretion to the SMBH. (Color online)

pressure. In our three-dimensional simulations, the height of the cloud is reduced to 1/100 of the initial value at the pericenter, resulting in a decrease of the effect of the ram pressure by a similar factor (see subsection 4.1). The total amount of accreted mass from the gas cloud up to AD 2023.5, the first ten years from the pericenter passage, is 15% of the cloud mass for Run 1. This accretion rate of Run 1 is comparable to that obtained in a two-dimensional simulation (Schartmann et al. 2012). Since the gas cloud in our three-dimensional simulation is vertically compressed, one might expect a much lower accretion rate. The main reason for this high accretion rate is that in our model the “ambient” gas is accreted to the SMBH, carrying the gas removed from the cloud. In the two-dimensional simulation of Schartmann et al. (2012), the ambient gas is pinned to the original position. Note that the higher accretion rate of the hot ambient gas indicates that, even if we assumed a relatively high density for the halo gas, it is probably difficult to observe the change of the activity of Sgr A* due to this additional accretion.

The overall evolution of the accretion rate strongly depends on the assumed density of the hot atmosphere. When we reduced the hot gas density by a factor of 10,
the accretion rate decreased by the same factor. The total amount of accreted mass during the first ten years from the pericenter passage became $\sim 2\%$ of the original cloud mass. In the run with no halo gas, no gas is accreted to the SMBH.

Figure 3 shows the evolution of the bolometric luminosity of the cloud, for three different models. We integrated the cooling rate of the gas particles in the process of simulations. Note that we neglect the emission from the gas absorbed by Sgr A*, because the accretion around Sgr A* is expected as RIAF. In all three runs the luminosity peaks at the time of pericenter passage. Before the pericenter passage, the luminosity is almost constant for the standard run, but goes down for the other two runs. In the case of the standard run, friction with the hot gas supplies thermal energy to the cloud, and the luminosity is kept nearly constant. For the other runs, the hot gas is much less dense and the heating effect is much smaller. However, the model variation vanishes when we assume a much stronger heating rate which is adequate to reproduce the environment of the galactic center region (see subsection 4.2). The peak luminosity and its duration are practically independent of the assumption about hot atmosphere. This result is quite natural, since the peak luminosity comes mainly from the tidal compressional heating of the cloud and has nothing to do with the interaction with the atmosphere. On the other hand, the interaction with the hot atmosphere keeps the luminosity high for years before and after the pericenter passage. We give a rough estimate of the effect of ram-pressure heating in subsection 4.1.

We can estimate the total amount of energy generated by tidal compressional heating in the following way. For the sake of simplicity, let us assume that the gas moves freely until it reaches the equatorial plane, where it converts all the kinematic energy of its vertical motion to thermal energy. This is, of course, not a realistic assumption, since the gas is heated due to compression and emits radiation. Therefore, strictly speaking, what is given below is the upper bound. The vertical velocity is given by $V_v = V_a \tan \iota$, where $V_a$ is the velocity at the ascending node and $\iota$ is the inclination. If we assume that the cloud was still spherical at around AD 2000, when the cloud was around one of the vertices, we have

$$V_v \approx 440 \left( \frac{V_a}{5300 \text{ km s}^{-1}} \right) \left( \frac{R_c}{125 \text{ au}} \right) \left( \frac{1500 \text{ au}}{R_b} \right) \text{ km s}^{-1},$$

for a gas element 125 au away from the orbital plane at AD 2000. Here, $R_c$ is the radius of the cloud when the cloud is on the minor axis of its orbit and $R_b$ is the distance to the vertex in the semiminor axis. By integrating the energy over the spherical cloud of radius $R_c$, we have

$$\frac{dE_t}{dt} \approx 2.2 \times 10^{35} \left( \frac{V_a}{5300 \text{ km s}^{-1}} \right)^2 \left( \frac{1500 \text{ au}}{R_b} \right)^2 \times \left( \frac{M_c}{3M_\odot} \right) \left( \frac{R_c}{125 \text{ au}} \right)^2 \left( \frac{1 \text{ yr}}{\tau} \right) \text{ erg s}^{-1},$$

where $M_c$ is the cloud mass. We assume that the vertical velocity is zero at that moment. In other words, we assume

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**Fig. 3.** Bolometric luminosity as a function of time. Panel a shows the time evolution of the luminosity from AD 1995 to 2030, while panel b shows it from AD 2011.5 to 2014.5. The solid black, red dashed, and blue dot-dashed curves are the results from simulations with the standard high-density atmosphere (Run1), with a low-density atmosphere (Run2), and no atmosphere (Run3), respectively. The green horizontal line indicates the expected luminosity of $9.2 \times 10^{33} \text{ erg s}^{-1}$ under the strong heating rate with $G_0 = 1.7 \times 10^7$. See the text in subsection 4.2. (Color online)
that the ascending node coincides with the pericenter. The duration of the energy release, \( \tau \), is about one year, as we can see in figure 3.

The radiative energy loss rate of the cloud is given by

\[
\frac{dE_{\text{cooling}}}{dt} \approx 1.1 \times 10^{39} \left( \frac{n_H}{10^5 \text{ cm}^{-3}} \right) \left( \frac{M_c}{3 M_\odot} \right) \text{ erg s}^{-1}. \tag{5}
\]

Here, we used a cooling coefficient of \( \Lambda \approx 10^{-22} \text{ erg cm}^3 \text{ s}^{-1} \) at a gas temperature of \( 10^4 \text{ K} \) (Sutherland & Dopita 1993). Since the cooling rate is sufficiently large, it is possible to keep the temperature of the cloud at \( \sim 10^4 \text{ K} \) (see also figure 4), and therefore the emission mostly appears in hydrogen recombination lines.

This simple estimate is in agreement with the total amount of radiation in our detailed simulations, although the actual evolution process would be much more complex. Note that the total amount of radiation depends on the height and vertical velocity structure of the cloud. For example, if the compression velocity is zero at the apocenter, the inclination would be smaller by a factor of a few, resulting in the decrease of the total luminosity by about one order of magnitude.

Figure 4 shows the distributions of temperature and brightness, for selected moments. Here, only the gas component which is initially associated with the gas cloud is considered. The main body of the gas cloud is heated by the compression, but the temperature remains at \( \sim 10^4 \text{ K} \) due to the very efficient radiative cooling of ionized hydrogen through recombination lines. The most luminous region is several hundred au in size. It is most likely to be observable from the outside in the near-IR, which does not significantly suffer from dust extinction effects.

4 Discussion and summary

4.1 Contribution of ram pressure in three-dimensional simulations

The ram pressure of the hot gas adjacent to the cloud is evaluated as

\[
P(r) = \rho_{\text{hot}}(r)v_c(r)^2, \tag{6}
\]

where \( \rho_{\text{hot}} \) is the density of the hot ambient gas and \( v_c \) is the velocity of the cloud relative to the gas. When we assume that part of the work on the pressure force is converted to the thermal energy of the cloud, the heating rate is

\[
\frac{dE_{\text{ram}}}{dt} = C \sigma P(r)v_c(r) = C \sigma \rho_{\text{hot}}(r)v_c(r)^3, \tag{7}
\]

where \( \sigma \) is the cross-section of the cloud, i.e., the size of the cloud projected to the plane perpendicular to the motion of the gas, and \( C \) is the conversion efficiency. By using the density profile of the hot ambient gas [equation (1)] and the relation between \( r \) and \( v_c \) [see equation (1) in
Burkert et al. 2012], we have
\[
\frac{dE_{\text{ram}}}{dt} \approx 8.2 \times 10^{33} C_{\text{hot}} \left( \frac{\sigma}{\pi (125 \text{ au})^2} \right) \left( 6 \times 10^{16} \text{ cm} \right) \\
\times \left[ \left( \frac{6 \times 10^{16} \text{ cm}}{r} \right) - 0.46 \right]^{3/2} \text{ erg s}^{-1}. \tag{8}
\]
We can see that the heating rate depends both on the distance from the SMBH and on the cross section of the cloud, i.e., \(r\) and \(\sigma\). Thus, to estimate the time variation of the heating due to the ram pressure, we need to estimate the time variation of the cross section.

As an example, we evaluate the ram-pressure heating rate at the pericenter. From figure 1, the cross section of the cloud at the pericentre is \(\sigma_{\text{AD} \ 2013.5} \sim 1 \text{ au} \times 40 \text{ au} = 40 \text{ au}^2\). The thickness of 1 au is affected by the resolution limit, and in reality the cloud is probably even thinner. Hence, the estimate below gives the upper limit. Substituting this value and \(r = r_{\text{AD} \ 2013.5} = 4 \times 10^{15} \text{ cm}\) into equation (8), we have
\[
\left( \frac{dE_{\text{ram}}}{dt} \right)_{\text{AD} \ 2013.5} \leq 5.6 \times 10^{33} C_{\text{hot}} \text{ erg s}^{-1}. \tag{9}
\]
Even when we adopt \(C \equiv 1\), this value is nearly two orders of magnitude smaller than that by tidal heating [see equation (4)]. The ram pressure is not the primary source of the luminosity of the cloud.

As another example, we evaluate equation (8) at AD 2000, where \(r_{\text{AD} \ 2000} = 6 \times 10^{16} \text{ cm}\). We assume that the cloud shape maintains the original spherical shape at this moment. Therefore, \(\sigma_{\text{AD} \ 2000} \sim \pi (125 \text{ au})^2\). By substituting these values, we obtain
\[
\left( \frac{dE_{\text{ram}}}{dt} \right)_{\text{AD} \ 2000} \approx 3.3 \times 10^{33} C_{\text{hot}} \text{ erg s}^{-1}. \tag{10}
\]
This rate is about three times higher than the result of our simulation. If we assume \(C \sim 0.3\), the ram-pressure heating fairly well explains the luminosity before the pericenter passage in our simulation.

### 4.2 Cloud luminosity before the pericenter passage

As described in sections 2 and 3, the adopted heating rate due to far-UV in our simulations was too low compared to the expected value. Here, we discuss the expected bolometric luminosity before the pericenter passage.

According to Bakes and Tielens (1994), the heating rate due to photoelectric heating by the far-UV field is
\[
n_{\text{HI}} \Gamma = 10^{-24} n_{\text{HI}} G_0 \epsilon_0 \text{ erg cm}^{-3} \text{s}^{-1}. \tag{11}
\]
where \(G_0\) is the coefficient of the heating rate and \(\epsilon_0\) is the efficiency; we consider this to be a constant value 0.05, although it depends weakly on \(G_0\), \(T\), and \(n_{\text{HI}}\) (Bakes & Tielens 1994). Thus the heating rate of the cloud is
\[
\frac{dE_{\text{heating}}}{dt} \approx 5.4 \times 10^{28} \left( \frac{M}{3 M_\odot} \right) \left( \frac{G_0}{10^2} \right) \left( \frac{\epsilon_0}{0.05} \right) \text{ erg s}^{-1}. \tag{12}
\]
As discussed in section 2, we could not use \(G_0 > 10^4\), and the actual value we used was \(10^4\). This value is quite low, and hence we cannot observe the effect of the heating in figure 3.

The expected value of \(G_0\) is \(\sim 1.7 \times 10^7\), which gives a heating rate of \(9.2 \times 10^{13} \text{ erg s}^{-1}\). The green horizontal line in figure 3 indicates this luminosity. In this case, the heating rate is always larger than that by the ram pressure. Thus, far-UV heating should be the primary source of the cloud luminosity before the pericenter passage, and all runs show the same and constant luminosity. The time-independent luminosity is consistent with the observations (see also subsection 4.3).

### 4.3 Luminosity in the Brγ line

Based on our simulation results, we discuss Brγ magnification during the pericenter passage. Since the main cooling mechanism of the gas cloud is the line cooling, we computed the ratio of the Brγ line luminosity to the total emission-line luminosity, \(F\). For this computation, we used the publicly available code Cloudy ver. c10.00 (Ferland et al. 1998).

We assumed a compressed gas with a hydrogen density of \(10^6 - 10^8 \text{ cm}^{-3}\), solar chemical abundances, and typical grains. Then we computed the emission-line spectrum when this gas is heated to \(2 \times 10^4 \text{ K}\). We found that \(F \sim 0.1\%\).

By multiplying \(F\) by the bolometric luminosity, we have a Brγ luminosity of several \(\times 10^{32} \text{ erg s}^{-1}\) at AD 2013.5. According to Gillessen et al. (2012, 2013a), the intrinsic luminosity of the Brγ line from G2 is 0.166%–0.2% of the solar luminosity, \(\sim 7 \times 10^{36} \text{ erg s}^{-1}\) during AD 2004–2012. Thus the Brγ luminosity at the peak will reach nearly 100 times of observed values before the pericenter passage.

Applying the value of \(F\) to the expected luminosity before the pericenter passage that we obtained in subsection 4.2, we obtain a constant Brγ flux of \(\sim 10^{-3} L_\odot\). This value is consistent with the observational results that the Brγ flux is \(\sim 2 \times 10^{-3} L_\odot\), and almost constant during the nine years since AD 2004 (Gillessen et al. 2012, 2013a, 2013b).

### 4.4 Peak bolometric luminosities with different orbits

So far four studies have reported on the orbital information revealed about G2, and there are some variations. Here,
we evaluate the peak luminosities of the cloud due to tidal compression in these orbits.

Table 2 summarizes the orbital information of four studies (Gillessen et al. 2012, 2013a, 2013b; Phifer et al. 2013), and the expected peak luminosities evaluated by equation (4). Note that we assumed the same duration for all orbits. In this table, we can see that the variations of the expected peak luminosities have a factor of three at most. The orbit reported by Phifer et al. (2013) gives the highest luminosity, reflecting the highest eccentricity and the closest pericentric distance.

We also note that the time for which the cloud will stay around the pericenter decreases when $V_n$ increases. As a result, the rise and decay of the light curve become steeper and the duration decreases. This should change the peak luminosity of the light curve, but we do not take this point into account in Table 2. Simulations with different orbits are necessary for confirming concrete expectations, and we will show them in the near future.

4.5 Summary

We have performed fully three-dimensional simulations of the evolution of the G2 cloud. Our result differs from the result of previous two-dimensional simulations in two ways: (i) strong vertical compression leads to the heating up and flaring up of the cloud at the first pericenter passage, and (ii) because of this compression, ram-pressure drag from the hot atmosphere is ineffective in removing the energy and angular momentum of the cloud.

In our standard model, the peak luminosity would reach ∼100 times the solar luminosity. The luminosity depends on the assumed internal-velocity structure of the cloud, and thus might be fainter by one order of magnitude. Since the peak luminosity is from tidal compressional heating, it does not depend on the assumption about the structure of the hot atmosphere around the SMBH. We therefore believe that our prediction is reasonably robust.

The increase of the luminosity of the cloud would be detectable in near-IR bands about six months before the time of near-IR pericenter passage. In parallel, the increase of the vertical velocity is probably observable as a line broadening. Since the vertical velocity should strongly depend on the position of the gas on the orbit, it is very important to measure the variation of the velocity profile both in space and in time.

Detailed comparisons between high-accuracy three-dimensional calculations and observations will help us to understand the nature of the cloud and how the cloud will interact with the SMBH.

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