MONITORING THE DUSTY S-CLUSTER OBJECT (DSO/G2) NEAR THE GALACTIC CENTER BLACK HOLE: MODEL PREDICTIONS FOR Brγ ENERGY SHIFT DURING THE PASSAGE

Michal Zajaček[1,2,3], **Vladimír Karas**[3], **Andreas Eckart**[2,1], **Monica Valencia-S.**[2]

[1] *Max-Planck-Institut für Radioastronomie (MPIfR), Auf dem Hügel 69, D-53121 Bonn, Germany,*
[2] *I. Physikalisches Institut der Universität zu Köln, Zülpicher Strasse 77, D-50937 Köln, Germany,*
[3] *Astronomical Institute, Academy of Sciences, Boční II 1401, 14100 Prague, Czech Republic.*

Max-Planck-Institut für Radioastronomie
Astronomical Institute of the Czech Academy of Sciences
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Dusty S-cluster Object (DSO/G2) has approached the supermassive black hole at the center of the Galaxy and its passage through the peribothron was monitored by the ESO VLT/SINFONI observations taken in the near-infrared K-band. The profile and the energy shift of Br-γ spectral line can be employed to further constrain the nature of this event. We update and discuss the model predictions for different scenarios: a core-less cloud versus an enshrouded star with a partially disintegrating envelope, potentially forming a bow shock due to stellar outflow. **A comparison of observations with model predictions shows that the DSO is a star rather than a core-less cloud.**

Introduction

The hydrogen emission line Brγ (produced by transition from level 7 to level 4) is frequently detected in active galactic nuclei (AGN) and generally indicates the presence of HII regions and indirectly the occurrence of massive OB stars that are needed to ionize the nuclear region. Thus it serves as an indicator of young star clusters formed recently during a star-formation episode.

Besides the role of the indicator of the ionized gas in nuclear regions, Brγ emission line is frequently detected in young stellar systems (YSOs); its occurence is $\sim$ 70–75% and it seems to be associated with the infall and accretion of material onto YSOs (see e.g. Ilee et al., 2014). In fact the correlation between Brγ emission-line luminosity and the accretion luminosity of YSOs is found to be relatively tight. The empirical relation between emission line and accretion luminosities is based on various signatures of accretion luminosity (Hα luminosity, optical and UV excess). The recent fit is as follows (Alcalá et al., 2014),

$$\log(L_{\rm acc}/L_{\odot}) = \zeta_1 \log[L({\rm Br}\gamma)/L_{\odot}] + \zeta_2\,. \tag{1}$$

with $\zeta_1 = 1.16 \pm 0.07$ and $\zeta_2 = 3.60 \pm 0.38$.

For extragalactic sources we may only detect integrated flux of the nuclear region, whereas for the Galactic centre of the Milky Way individual gaseous components and stars can be resolved and analysed. The recent challenge is the observation of a fast-moving, infrared-excess dusty S-cluster object (hereafter denoted as DSO) that has passed the peribothron in early 2014. Its character was puzzling - mainly two scenarious were discussed: a core-less gas and dust cloud or a dust-enshrouded star.

However, the compact line profile and the constant luminosity of the resolved Brγ emission line of the source provided crucial information to identify the object, see Fig. 2 (right panel). **In combination with the detection in K-band continuum (Eckart et al., 2014) the character of the DSO must be stellar and it seems to be a young star, possibly accreting material from an inner accretion disc.**

Figure 1: **Left:** Orbital trajectory of the DSO in the S-cluster. **Middle:** Temporal evolution of the line-of-sight velocity. **Right:** Temporal evolution of the velocity magnitude. Orbital elements were taken from the fit in Valencia-S. et al. (2015).

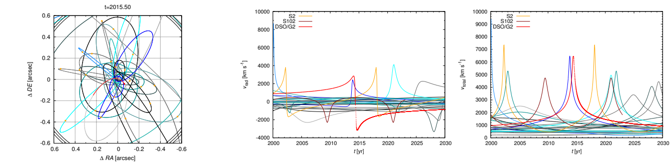
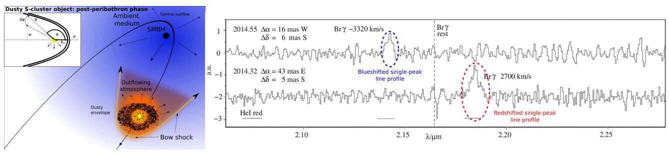


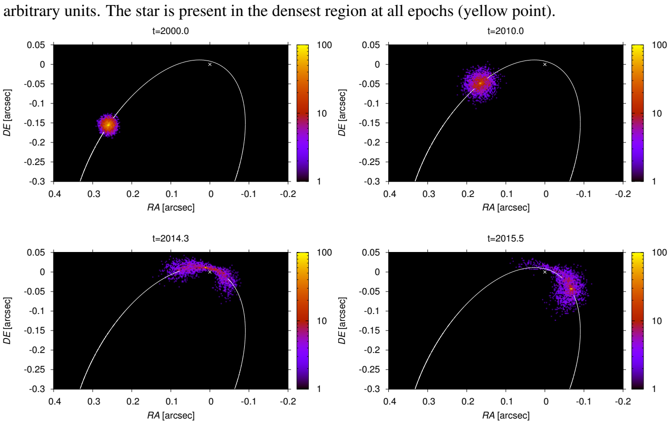
Figure 2: **Left:** Illustration of a young star with both the inflow and the outflow. A bow shock is formed due to relative supersonic motion. **Right:** Observed spectra of Brγ emission line during the pre-pericentre (red-shifted profile in red ellipse) and the post-pericentre orbital phase (blue-shifted profile in blue ellipse). Spectra adopted from Valencia-S. et al. (2015).



Results: Model of a young star associated with the DSO

Passage of a star with circumstellar envelope. The stellar scenario for the DSO was proposed by Eckart et al. (2013) and numerically analyzed in Zajaček et al. (2015). The structure of the circumstellar envelope of a pre-main-sequence star can be complex, with both the inflow and the outflow potentially present, see Fig. 2 (left panel). The density naturally increases towards the star (material can be present in the accretion disc, accretion columns and wind). The material outside the critical tidal radius is strongly perturbed (see Fig. 5, left panel) and escapes from the star. However, inside the pericentre Roche lobe of the star the density distribution is only slightly perturbed and is stable along the orbit.

Figure 3: The orbital evolution of a star with a circumstellar envelope whose initial density profile decreases as r^{-2}. The envelope initially extends from 0.01 AU up to 10 AU from the star whose mass is 1.5 $M_{\odot}$. The FWHM of velocity dispersion in the envelope (with potentially both the inflow and outflow) is set to 100 km s^{-1}. The colour-coded axis displays the density of circumstellar matter in arbitrary units. The star is present in the densest region at all epochs (yellow point).



We perform model calculations of line profiles assuming that the stellar envelope is optically thin for Brγ emission, see Fig. 4. The line position and shape are affected by (a) the motion of the star and (b) by the tidal evolution of outer parts of the envelope. For comparison, we compute the evolution of the line profile for the model of a core-less cloud, which was assumed in Gillessen et al. (2012) and Gillessen et al. (2013). While the stellar model predicts emission with one prominent peak at all epochs, the core-less cloud model predicts a double-peak emission line profile around the pericentre passage. Observations by Valencia-S. et al. (2015) clearly favour the stellar model, since no prominent double-peak emission line was detected around the pericentre passage, see Figs. 2–4.

Due to the tidal field of the supermassive black hole the line profile in all cases is intrinsically asymmetric and skewed, which is not considered in publications where a Gaussian profile is automatically assumed.

Constraints on a star associated with the DSO. Detection of only one clear peak of *Brγ* emission (see Fig. 4 and analysis in Valencia-S. et al., 2015) indicates that the character of the DSO is stellar rather than nebulous. In that case Brγ emission originates in the environment that is not strongly affected by the gravitational potential of the SMBH: **accretion columns** from a disc inside the Roche lobe of the star and/or **bow-shock** emission due to a supersonic motion of the star (Zajaček et al., 2015) are potential candidates, see Fig. 2 for illustration of different contributions. The left panel in Fig. 5 shows the temporal evolution of the tidal (Hill) radius for $1 M_{\odot}$ star, beyond which the circumstellar material is tidally perturbed and may escape the vicinity of the star. The tidal radius for a star around the SMBH is typically 0.1 AU $\lesssim r_{\rm t} \lesssim$ 1 AU at the peribothron. Hence, a small accretion disc can survive repetitive passages around the SMBH. The right panel in Fig. 5 represents HR diagram of pre-main-sequence stars. The spectral decomposition of the DSO puts an upper limit on its bolometric luminosity ($L_{\rm DSO} \lesssim 30\,L_{\odot}$), which automatically limits the mass as well as the radius of the putative star: $M_{\rm DSO} \lesssim 3\,M_{\odot}$, $R_{\rm DSO} \lesssim 10\,R_{\odot}$.

Figure 4: Comparison of two scenarios for the temporal evolution of Brγ emission of the DSO: **star with envelope (left panel)** and **core-less cloud (right)**. **Observations by Valencia et al. (2015) favour the stellar model since no clear double-peak Brγ emission line was detected around the pericentre passage.**

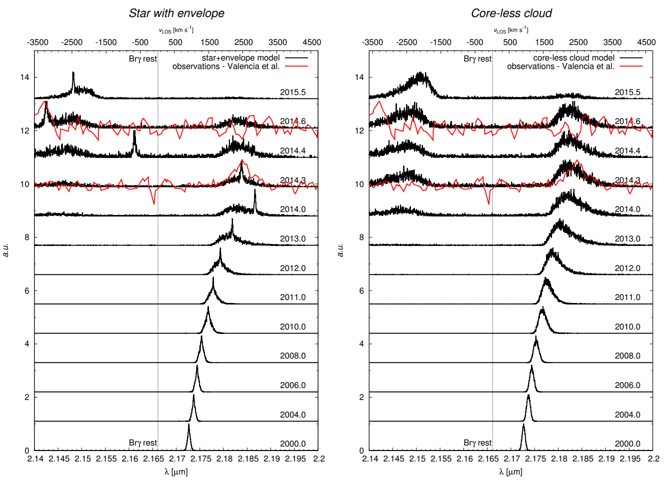
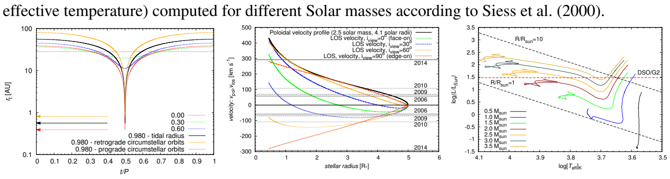


Figure 5: **Left:** Temporal evolution of tidal (Hill) radius for orbits of a 1 $M_{\odot}$ star around the SMBH. **Center:** Maximum line-of-sight velocity profiles of accretion streams moving from a disc along magnetic streamlines as a function of the distance from a 2.5 $M_{\odot}$ star. **Right:** HR diagram (luminosity–effective temperature) computed for different Solar masses according to Siess et al. (2000).



Conclusions. Based on the comparison of the observed line profiles near the peribothron passage with model predictions we propose that the DSO is a star rather than a nebula. The observed characteristics of Brγ broad emission line are reproduced within the framework of a young-star model, where the emission originates in accretion columns from a disc surrounding the star combined with stellar/disc winds. Additional contribution to the emission may be provided by the bow shock forming ahead of the star. The stellar scenario for the DSO is also consistent with the non-detection of flux enhancement in the radio/mm domain above the quiescent emission of Sgr A*.

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Send offprint requests to: **M. Zajaček** (`zajacek@ph1.uni-koeln.de`).