galaxies

MDPI

Article

Polarization: A Method to Reveal the True Nature of the Dusty S-Cluster Object (DSO/G2)

Banafsheh Shahzamanian [1,*], Andreas Eckart [1,2], Michal Zajacek [1,2], Monica Valencia-S. [1] and Nadeen B. Sabha [1]

[1] I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany; eckart@ph1.uni-koeln.de (A.E.); zajacek@ph1.uni-koeln.de (M.Z.); mvalencias@ph1.uni-koeln.de (M.V.-S.); sabha@ph1.uni-koeln.de (N.B.S.)

[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

* Correspondence: shahzaman@ph1.uni-koeln.de

Received: 15 November 2017; Accepted: 11 January 2018; Published: 17 January 2018

Abstract: There have been different scenarios describing the nature of a dusty source, noted as Dusty S-cluster Object (DSO) or G2, orbiting around the Galactic centre super-massive black hole. Observing the polarized continuum emission of this source provides information on its nature and geometry. We show that this source is intrinsically polarized with polarization degree of 30%, implying that it has a non-spherical geometry, and a varying polarization angle in the ambient medium of the black hole. Its main observable properties can be well described and modeled with a pre-main-sequence star forming a bow shock as it approaches the Sgr A* position.

Keywords: Galaxy: centre; polarization; stars: pre-main-sequence; radiative transfer

1. Introduction

The Galactic centre is a great laboratory to study stars, their formation and proper motion, and their interaction with their environment. The Dusty S-cluster Object (DSO/G2) is a peculiar source in the Galactic centre which orbits on a highly eccentric orbit around Sagittarius A* (Sgr A*) which is associated with a super-massive black hole $M_{BH} \simeq 4 \times 10^6 M_\odot$ [1–4]. It has been described as a core-less dusty gas cloud named as G2 [5] and also as a Dusty S-cluster Object (DSO) with a stellar nature [6]. This source has been of great interest since its periapse distance is only 2000 Schwarzschild radii. It could have affected the accretion flow of the super-massive black hole during its fly-by and therefore causing possible variabilities of Sgr A* emission. It was found in L'-band (3.8 µm) as a bright source [5]. It has the temperature of $T_{DSO/G2} = (874 \pm 54)$ K and the radius of the optically thick photosphere of $R_{DSO/G2} = (0.31 \pm 0.07)$ AU [7].

The DSO/G2 has a strong emission of Brγ, which remained compact before and after the periapse passage in the spring of 2014, that shows the existence of outflow or inflow from/to a stellar core. The increase of a Brγ line width also shows that it is a young accreting star surrounded by a dusty envelope [8]. It is an infrared-excess source compared to the main-sequence stars and has a magnitude of 18.5 in K_s-band (2.2 µm) continuum [6,9]. Since it is a very faint source in a crowded stellar region, it is not easy to disentangle its emission from the stars around it, therefore one needs to consider all its properties such as spectral properties, orbital dynamics, and polarimetry in order to conclude on its nature. We can understand more about the radiative processes and the internal geometry of the source by studying the polarization properties of the light coming from it. In the near-infrared, the intrinsic polarization can be produced by (Mie-) scattering on dust grains in a dusty stellar envelope. If the source has a non-spherical geometry then the overall polarization is not zero and depending on the geometry of the source significance of the polarized emission varies.

2. Analysis and Results

Polarization analysis of DSO/G2 can help us to investigate its geometry and dust properties. We measured the polarization parameters of this source and obtained that it has a significant linear polarized emission in near-infrared K_s-band. The data was taken by NACO at the Very Large Telescope of the European Southern Observatory between 2008 and 2012 . The DSO/G2 shows a polarization degree of around 30%, which is noticeably higher than the foreground polarization degree of 6.1% measured on the surrounding stars, and a variable polarization angle when the source moves towards the periapse [9]. We also studied its light curve and found out that it does not show any flux density variability in our data.

Our Monte Carlo simulations shows that the significance of the linear polarization measurements is larger than 1–1/100,000. The polarization degree during the observing years (2008–2012) does not vary within uncertainties. On the other hand, the polarization angle varies due to the internal and/or external influences (See Figure 1 left). The observed polarization quantities are trustworthy measurements and show the intrinsic properties of a source when the S/N is high. We obtain that the DSO/G2 polarization measurements are statistically significant for different observing years of 2008, 2009, and 2012. This source is a point-like source in our continuum polarimetry mode observations and its significant intrinsic polarization exhibits its non-spherical geometry. Our findings about the large infrared excess ($K_s - L' > 3$) and polarized emission lead us towards the modeling of the source as a dust enshrouded star with bipolar cavities and a bow shock [7,9,10].

We used a 3D Monte Carlo radiative transfer code Hyperion [11] in order to model the DSO/G2. We considered Mie scattering as the process responsible to create the polarized emission which is the photon scattering on spherical dust grains. This code allows us to construct the polarization maps and also to calculate the polarization degree and angle. We could then compare our radiative results of the DSO/G2 model with the observational results of [9]. In our model, the bipolar outflows and a bow-shock layer break the spherical symmetry and create the polarization degree of 30% [7] (See Figure 1 right).

We could also model the change in polarization angle by considering the variation of the circumstellar configuration. The wobbling of the accretion disk in the presence of the gravitational field of Sgr A* can lead to the change in the orientation of the bipolar outflow [9]. Another scenario for the non-spherical geometry of the source can be the prolongation of the gaseous environment due the tidal forces rather than the described model. However, the tidal stretching of the source along its orbit was not observed in continuum and line emission during its periapse passage [8,12].

The fly-by of dusty sources, such as DSO/G2, depending on their nature can have an effect on the accretion flow of Sgr A*. Sgr A* system has a rather stable geometry and accretion process based on studies by [13,14]. The authors showed that the measured preferred polarization angle of Sgr A* most likely exhibits its intrinsic orientation, i.e. a disk or jet/wind scenario associated with the black hole. The powerlaw slope of $\sim$4 for the number density of its near-infrared total flux density [15] and polarized flux density as well as the defined range in polarization degree show the stability of the accretion process of Sgr A* system during the past 8 years of study [13]. The DSO/G2 remained compact and its orbit keplerian during its closest approach to Sgr A* [8,12]. Therefore, this source had weak interactions with the super-massive black hole and did not lose a considerable amount of angular momentum and energy during and after its periapse passage [16].

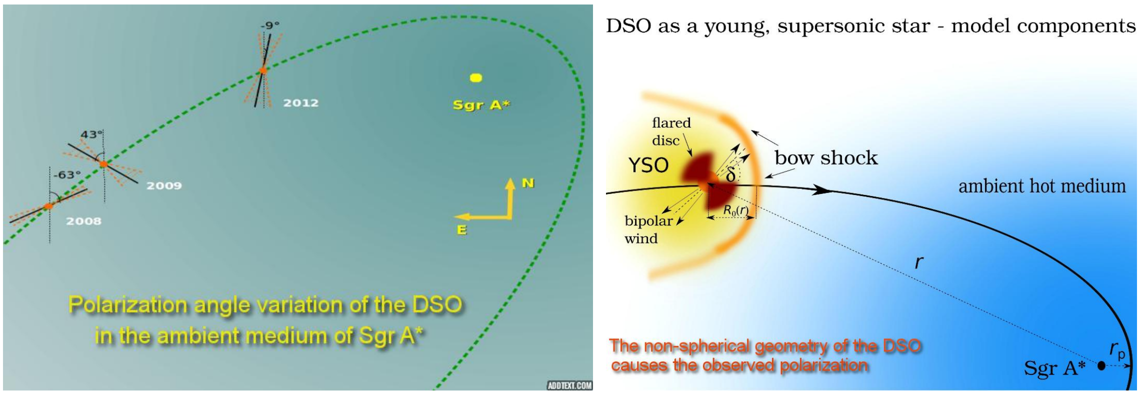

Figure 1. Left: The illustration of the Dusty S-cluster Object (DSO)/G2 polarization angle variation as it moves towards the position of Sgr A*. **Right**: The sketch of the composite stellar model of the DSO/G2 including: star, dusty envelope, bipolar wind, and bow shock (See [9] for more details).

Acknowledgments: This work was supported in part by the Deutsche Forschungsgemeinschaft (DFG) via the Cologne Bonn Graduate School (BCGS), the Max Planck Society through the International Max Planck Research School (IMPRS) for Astronomy and Astrophysics. Part of this work was supported by fruitful discussions with members of the Czech Science Foundation DFG collaboration (No. 13-00070J). We also received funding from the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement n312789; Strong gravity: Probing Strong Gravity by Black Holes Across the Range of Masses.

Author Contributions: B.S. analyzed the data, led the work, and prepared the manuscript with the active and needful collaboration of all the co-authors. In particular, the contribution of M.Z. was essential for the model presented. Other co-authors contributed to the observations, or to the analysis of the data from the observations listed here.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Eckart, A.; Genzel, R. Observations of stellar proper motions near the Galactic Centre. *Nature* **1996**, *383*, 415–417.
2. Eckart, A.; Genzel, R. Stellar proper motions in the central 0.1 PC of the Galaxy. *Mon. Not. R. Astron. Soc.* **1997**, *284*, 576–598.
3. Eckart, A.; Hüttemann, A.; Kiefer, C.; Britzen, S.; Zajaček, M.; Lämmerzahl, C.; Stöckler, M.; Valencia-S., M.; Karas, V.; García-Marín, M. The Milky Way's Supermassive Black Hole: How Good a Case Is It? *Found. Phys.* **2017**, *47*, 553–624.
4. Parsa, M.; Eckart, A.; Shahzamanian, B.; Karas, V.; Zajaček, M.; Zensus, J.A.; Straubmeier, C. Investigating the Relativistic Motion of the Stars Near the Supermassive Black Hole in the Galactic Center. *Astrophys. J.* **2017**, *845*, 22.
5. Gillessen, S.; Genzel, R.; Fritz, T.K.; Quataert, E.; Alig, C.; Burkert, A.; Cuadra, J.; Eisenhauer, F.; Pfuhl, O.; Dodds-Eden, K.; et al. A gas cloud on its way towards the supermassive black hole at the Galactic Centre. *Nature* **2012**, *481*, 51–54.
6. Eckart, A.; Mužić, K.; Yazici, S.; Sabha, N.; Shahzamanian, B.; Witzel, G.; Moser, L.; Garcia-Marin, M.; Valencia-S., M.; Jalali, B.; et al. Near-infrared proper motions and spectroscopy of infrared excess sources at the Galactic center. *Astron. Astrophys.* **2013**, *551*, A18.
7. Zajaček, M.; Britzen, S.; Eckart, A.; Shahzamanian, B.; Busch, G.; Karas, V.; Parsa, M.; Peissker, F.; Dovčiak, M.; Subroweit, M.; et al. Nature of the Galactic centre NIR-excess sources. I. What can we learn from the continuum observations of the DSO/G2 source? *Astron. Astrophys.* **2017**, *602*, A121.
8. Valencia-S., M.; Eckart, A.; Zajaček, M.; Peissker, F.; Parsa, M.; Grosso, N.; Mossoux, E.; Porquet, D.; Jalali, B.; Karas, V.; et al. Monitoring the Dusty S-cluster Object (DSO/G2) on its Orbit toward the Galactic Center Black Hole. *Astrophys. J.* **2015**, *800*, 125.

9. Shahzamanian, B.; Eckart, A.; Zajaček, M.; Valencia-S., M.; Sabha, N.; Moser, L.; Parsa, M.; Peissker, F.; Straubmeier, C. Polarized near-infrared light of the Dusty S-cluster Object (DSO/G2) at the Galactic center. *Astron. Astrophys.* **2016**, *593*, A131.
10. Zajaček, M.; Eckart, A.; Karas, V.; Kunneriath, D.; Shahzamanian, B.; Sabha, N.; Mužić, K.; Valencia-S., M. Effect of an isotropic outflow from the Galactic Centre on the bow-shock evolution along the orbit. *Mon. Not. R. Astron. Soc.* **2016**, *455*, 1257–1274.
11. Robitaille, T.P. HYPERION: An open-source parallelized three-dimensional dust continuum radiative transfer code. *Astron. Astrophys.* **2011**, *536*, A79.
12. Witzel, G.; Ghez, A.M.; Morris, M.R.; Sitarski, B.N.; Boehle, A.; Naoz, S.; Campbell, R.; Becklin, E.E.; Canalizo, G.; Chappell, S.; et al. Detection of Galactic Center Source G2 at 3.8 μm during Periapse Passage. *Astrophys. J. Lett.* **2014**, *796*, L8.
13. Shahzamanian, B.; Eckart, A.; Valencia-S., M.; Witzel, G.; Zamaninasab, M.; Sabha, N.; García-Marín, M.; Karas, V.; Karssen, G.D.; Borkar, A.; et al. Polarized light from Sagittarius A* in the near-infrared K_s-band. *Astron. Astrophys.* **2015**, *576*, A20.
14. Shahzamanian, B.; Eckart, A.; Valencia-S., M.; Witzel, G.; Zamaninasab, M.; Zajaček, M.; Sabha, N.; García-Marín, M.; Karas, V.; Peissker, F.; et al. Variable and Polarised Near-infrared Emission from the Galactic Centre. *Messenger* **2015**, *159*, 41–45.
15. Witzel, G.; Eckart, A.; Bremer, M.; Zamaninasab, M.; Shahzamanian, B.; Valencia-S., M.; Schödel, R.; Karas, V.; Lenzen, R.; Marchili, N.; et al. Source-intrinsic Near-infrared Properties of Sgr A*: Total Intensity Measurements. *Astrophys. J. Suppl. Ser.* **2012**, *203*, 18.
16. Park, J.H.; Trippe, S.; Krichbaum, T.P.; Kim, J.Y.; Kino, M.; Bertarini, A.; Bremer, M.; de Vicente, P. No asymmetric outflows from Sagittarius A* during the pericenter passage of the gas cloud G2. *Astron. Astrophys.* **2015**, *576*, L16.