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Direct imaging potential of outer companions of eclipsing binary stars with 4-meter telescope of the Eastern Anatolia Observatory (DAG)

F. Tezcan[1], **Ö. Baştürk**[2], **C. Yeşilyaprak**[3,4] **and S. Aliş**[5]

[1] *Atatürk University, Graduate School of Natural and Applied Sciences, Astronomy and Astrophysics, Erzurum, Türkiye (E-mail: fatosuyanik9@gmail.com)*

[2] *Ankara University Faculty of Science, Astronomy and Space Sciences, Ankara, Türkiye*

[3] *Atatürk University Faculty of Science, Astronomy and Space Sciences, Erzurum, Türkiye*

[4] *Türkiye National Observatories, DAG, Erzurum, Türkiye*

[5] *İstanbul University, Faculty of Science, Astronomy and Space Sciences, İstanbul, Türkiye*

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Abstract. Investigation of gravitationally bound objects to the binary star systems is crucial for understanding binary star formation and their orbital evolution. They also provide significant advantages in the empirical determination of the observational limits of a direct imaging system thanks to the wide range of spectral type and magnitude differences (contrast), and angular separations between binary components and their additional companions. In this study, the potential of direct imaging of these additional bodies proposed by various methods around binary stars with the brand-new 4-meter DAG telescope will be discussed. DAG Direct Imaging System (DGS) is composed of an active and adaptive optics system, a coronagraph, and an infrared imager to be operated in the near infrared wavelengths (<3 microns), for which the first light is expected to be acquired in 2025.

Key words: direct imaging – binary stars – multistellar systems – infrared observations

1. Introduction

Close binary star systems are often observed to have additional components gravitationally bound to the system. If the systems are hierarchical, the third body can maintain a stable orbit for an extended period. Hierarchical triples consist of an ”inner” binary star and a third star orbiting a common center of mass with the binary (Borkovits et al., 2015).

Formation of tertiaries in such systems can be explained by captures, insitu or ex-situ formation followed by subsequent migration theories. First- and second-generation formation theories are also considered for objects in the substellar mass regime, with formation timing classified as either simultaneous with or occurring after the common envelope ejection in post-common-envelope systems (Zorotovic & Schreiber, 2013). These tertiaries also affect the orbital evolution of the binary through mechanisms such as von Zepel-Kozai-Lidov cycles (von Zeipel, 1910; Kozai, 1962; Lidov, 1962).

In order to characterize a direct imaging system empirically, one needs the observations of objects spanning a wide range of spectral types, magnitudes, and angular separations. Hence, hierarchical triplets become the ideal objects for the task. In addition to the known hierarchicals, many additional bodies have been suggested around eclipsing binaries with different techniques, primarily with the Eclipse Timing Variations (ETVs) such bodies induce through the Light-Time Effect (LiTE). Eclipsing binaries are also advantageous because they are fainter during the eclipses enhancing the contrast. We are planning an observational project with DAG 4m telescope and its imaging system composed of an active coronograph (PLACID) to contribute to the 1) determination of its limits, 2) confirmation of suggested bodies and determination of their physical and orbital parameters, 3) statistical studies on the frequency of occurrence of such systems.

2. DAG direct imaging system

A limited number of additional components of binary star systems can be identified with the high-precision astrometric observations of the Gaia Space Telescope. Due to the limited angular resolution of Gaia, it is known that components with an angular distance below 2 arcseconds cannot be identified in a wide contrast range (Mugrauer, 2019). Most other direct imaging systems concentrate either on planet discovery programs and / or follow-up observations of Transiting Exoplanet Survey Satellite (TESS) to determine potential contamination sources. Therefore, systems that may have additional components around them need to be investigated with high contrast and angular resolution using direct imaging techniques.

The Eastern Anatolia Observatory (DAG) Telescope is being built in Türkiye (3170 m elevation), on the Karakaya peaks of Erzurum province. The DAG Telescope is also the largest telescope in the country with a 4-meter primary mirror diameter and 56-meter focal length (F/14.2) Ritchey-Chretien design (Yesilyaprak et al., 2022). The DAG Telescope has two selectable focal points called Nasmyth platforms. High-resolution photometric images will be obtained with the sensitive Infrared camera (¡ 3 microns - DIRAC (Zhelem et al., 2022)), Coronagraph (PLACID - (Kühn et al., 2021)) and Pyramid Adaptive Optics system (TROIA - (Keskin et al., 2022)) to be located on one of these platforms.

The coronagraph system planned to be used at the DAG Telescope will have an adaptively programmable liquid crystal structure (Programmable Liquid-crystal Active Coronographic Imager for the DAG Telescope - PLACID - Kühn et al. (2021)). It will be able to acquire images in a $7''x\ 7''$field at 1.6 microns (H band) and up to 2.15 microns (Ks). When used with adaptive optics, it will be able to obtain diffraction-limited, high-contrast images and will be used for direct imaging of exoplanets, interstellar matter, and multiple star systems. Some laboratory results listed in Table 1.

Table 1. The Programmable Liquid-crystal Active Coronagraphic Imager for the DAG Telescope PLACID

Observing Bands	H-Band: 1.63 μm, Ks-Band: 2.15 μm
SLM Specification	1920x1152 pixels, 8 bits
Field of View	$16''$x $9.6''$
λ/D at H-Band	85 mas
Optical Throughput	22 %
Raw Contrast at 2λ/D	$< 5.3x10^{-2}$
Raw Contrast at 5λ/D	$< 5.3x10^{-4}$

3. Potential observations of outer companions of eclipsing binaries

In its first years of operation of DAG, a significant time will be devoted to high contrast direct imaging. Hence, binary and multiple star systems with resolvable faint components can be targeted in such an extended observation window. With that in mind, a list of systems around which additional objects have been suggested primarily based on ETVs, the third light contribution observed in light curve solutions, and signals related to the third component in radial velocity profiles, has been compiled from the literature for the detection and confirmation of unseen additional components with the DAG DGS. The list is not final and objects may be added or removed during the study. We listed first 5 stars and their information in Table 2

We will first compile and / or derive the J, H, and K magnitudes for the binary systems and their additional components allowing us to have estimates on the expected contrast values. Based on the previous literature, ETV solutions, databases, and archives such as Gaia, HIPPARCOS, and Washington Double Star Catalogue (WDS), we are going to determine the expected positions (position angle and angular separation at a given time) of the additional objects in our list. The most promising systems will be selected from this list spanning a wide range of spectral types, contrasts, and angular separations to determine the limits of the DAG DGS.

Table 2. Five examples from our list of potential candidate systems, compiled based on their compatibility with DAG-DGS observations.

Object	Type	Ang.Sep.	Mag G	G Flux Ratio	Mag R	R Flux Ratio
GSC 1387-0475	Double or Multiple Star	0.70	10.45	5.97×10^{-1}	9.36	6.77×10^{-1}
LV Vir	Spectroscopic Binary	0.89	8.96	6.96×10^{-1}	8.02	9.86×10^{-1}
V829 Her	Spectroscopic Binary	1.19	13.12	6.47×10^{-2}	-	-
NSVS 12277727	Eclipsing Binary	1.55	15.38	1.31×10^{-1}	-	-
V508 Oph	Spectroscopic Binary	1.66	16.24	4.39×10^{-3}	-	-

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