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SDSS-PS1-GAIA: DISCOVERY OF FAST ECLIPSING SYSTEMS IN A SEARCH FOR EARTH-SIZE EXOPLANET AROUND WHITE DWARF

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ABSTRACT

white dwarf sample from Gaia DR2. SDSS observed each white dwarf in five filters. use SDSS colors to search for transits of exoplanets. discovery of a fast eclipse star

1. INTRODUCTION

Exoplanets are very common around lower main sequence stars (XX). The vast majority of these planet-hosting stars, including our sun, will evolve into white dwarf stars. Theoretically, it has long been suggested that planets close to the host stars cannot survive as the host stars evolve to the red giant branch (RGB) and asymptotic giant branch (AGB) (XX), but there are also suggested ways of how planets can survive the evolution of host stars (XX). Apart from this, new generation of planets may form around a white dwarf. This is plausible because (1) dust debris disks are very common around white dwarf (XX); (2) many white dwarfs show metal polluted atmosphere which are believed to caused by tidal disruption of astroids around white dwarf (XX).

Empirically, the presence of planets, old or new, around white dwarfs is still very uncertain. Searches of planets around white dwarfs have been carried out in different methods.

(1) Massive planets or brown dwarf may be found in the near-infrared where white dwarfs emit little light. Near-infrared photometry and spectrum have found several brown dwarfs around white dwarfs (e.g. Zuckerman & Becklin 1988; Burleigh et al. 2006; Mullally et al. 2007).

(2) Planets around pulsating white dwarfs can cause changes in the observed arrival time of the pulsations. This method is most sensitive to massive planets at wide orbits. Timing experiments around small sample of pulsating white dwarfs have found one $2M_{Jupiter}$ planet candidate (Mullally et al. 2008).

(3) Transits of planets can cause large variability due to the small size of white dwarfs. Because white dwarf radii are only $\sim$1% of the Sun, or about the same size as the Earth, even small Earth-sized planets can cause large transit depth. The characterization of the planetary atmospheres in transit system is also easier due to the small size of white dwarf (Loeb & Maoz). However, small size of white dwarf means small transit probability. In general, due to the low transit probability, thousands of white dwarfs need to be observed to find transits of rocky planets (Drake et al. 2010; Kilic et al. 2013).

Due to the large planet transit signal, planets around white dwarf can be searched as a by-product in many wide field imaging surveys targeting mainly for other science goals. In the Catalina Sky Survey, Drake et al. (2010) searched for planets around about 12,000 white dwarfs. Each object was observed a few to more than 250 times. They find 20 eclipsing systems, 3 of which have radii consistent with substellar objects and show no evidence of flux from the companion object in the available optical or near-IR data. Fulton et al. (2014) searched for eclipses of $\sim$ 1700 photometric selected white dwarfs in the 10 Pan-STARRS1 medium-deep fields spanning 70 $\deg^2$ on the sky. Each object was observed for about 1000-3000 times. They detected zero eclipses. Sluijs et al. (2017) studied a sample of 1148 WDs observed by K2 and placed limits on the occurrence rates of planets.

The SDSS camera worked in drift scan mode, opening its shutter for extended periods and imaging a continuous strip of the sky.

Drift scan mode of SDSS and gaia make short cadence light curves. SDSS 1-minute cadence. It has been noted that earth-like planets in the habitable zone of white dwarf have transit time of about 2 minutes.

In this paper, we search for planetary eclipses of $\sim$ 80,000 Gaia-selected white dwarfs in SDSS.

2. SEARCH METHOD AND CANDIDATES

2.1. *Gaia white dwarf catalog*

The Gaia data release 2 provides precise astrometry and optical colors for all sources across the full sky down to about Gaia G=20−21 magnitudes (Gaia Collaboration et al. 2018). This data allows the identification of white dwarfs in an absolute magnitude versus color (Hertzsprung-Russell, H-R) diagram. We adopt a recent catalog of white dwarf candidates (Nicola Pietro Gentile Fusillo et al. 2018) selected from the H-R diagram based on Gaia parallax and photometry. This catalog includes $\sim$ 260,000 high-confidence white dwarf candidates and $\sim$

79,989 white dwarfs are covered by SDSS images.

2.2. *SDSS and PS1 photometry*

The SDSS imaging camera took a total of around 35,000 deg^2 of images, covering a unique footprint of 14,055 deg^2 of sky. Each sky region have images in five filters observed in the same time sequence: *r, i, u, z and then g*. Each filter is separated by 71.72 seconds of drift scan time. More detail about SDSS image is available in the SDSS website and SDSS early data release paper (Stoughton et al. 2002).

The Pan-STARRS1 (PS1) 3Pi survey covers 30,000 deg^2 of sky north of Declination -30 degree in 5 filters (*grizy*) with approximately 10 exposures per filter over a four-year time span (Chambers, K.C., et al. 2017). The average photometry of PS1 sources provide good reference points for the search of short-time scale variations.

By comparing the SDSS and PS1 photometries of each source, we can get the relative variabilities in the SDSS *griz* bands. Then we can get a time sequence of four variability measurements separated by about one minute. We can search for one-minute timescale transit using this method.

2.3. *Crossmatch Gaia white dwarfs with SDSS and PS1 photometry*

We matched the Gaia white dwarfs with SDSS DR12 photometric catalog *photoObjAll* using their coordinates. To get reliable SDSS photometry, we require each SDSS entry to satisfy the following criteria: 1) the object is a run primary object (resolveStatus & 0x01 == 1); 2) the data was taken under photometric conditions (calibStatus_ugriz == 1); 3) the object flags are *not* SATURATED, INTERP_CENTER, PSF_FLUX_INTERP, COSMIC_RAY, NOTCHECKED, PEAKCENTER, BAD_COUNTS_ERROR, EDGE, DEBLENDED_AS_MOVING, or BAD_MOVING_FIT; 4) either g or r band PSF magnitude has good signal-to-noise ratio (PSF magnitude error < 0.15). We get a matched SDSS catalog of 106,722 uniq observations of 60,406 Gaia white dwarf candidates. 22,264 white dwarfs have multiple SDSS observations. We use the SDSS PSF magnitudes in the following analysis.

We also matched the Gaia-SDSS white dwarfs to the PS1 data release 1 database. The matched Gaia-SDSS-PS1 catalog includes a total of 60,065 uniq white dwarfs. We use the PS1 mean PSF magnitudes in the following analysis.

2.4. *Selection of eclipse candidates*

Because the eclipse or transit of white dwarf cause large amplitude of variation, our first step is to select candidate with large variation in each filter. For the *g (or r, i, z)* filter, we use the PS1 photometry as reference and require the SDSS photometry of candidate is one magnitude fainter than PS1 photometry. For the u filter, because there is no PS1 data, we require there are multiple SDSS observations. We use the brightest u-band observation as reference and select candidates with variation larger than one magnitude. After the first step, we get a total of 205 uniq white dwarf candidates.

Some candidates are selected because their SDSS photometries are incorrect for some reasons. Our next step is to do forced aperture photometry on the SDSS images. We use a 2 arcsec radius aperture and require the aperture magnitudes are one magnitude fainter than the referencing magnitudes. After this step, we get 66 uniq white dwarf candidates.

Then we check the images and light curves of these candidates one by one. We calculate the light curves of brightness relative to the referencing photometry. 55 candidates are further removed for two reasons: 1) image quality problem; 2) wrong crossmatch due to the object is a visual binary system within the 2 arcsec matching radius. Another 6 candidates are probably long timescale variable sources between SDSS and PS1, because the light curve is not consistent with an eclipse or transit event. The remaining 5 candidates have good images and their SDSS light curves show large variations within a few minutes.

3. WHITE DWARF ECLIPSING / TRANSITING SYSTEMS

We found five eclipsing / transit white dwarf candidates. In figure 1 and table 1, we show their light curves and photometries. In the light curves, we show the referencing observations and the observations with eclipse events. We have done follow-up observations of two candidates shown in the following sections. Below is brief information of the other three candidates.

(1) SDSS J155256.11+125444.1, also named NN Serpentis, is a previously known pre-cataclysmic binary (Parsons et al. 2010). Studies of the long-term eclipse time variations suggested that there are two planets orbiting this binary system (Beuermann et al. 2010). orbital period? The SDSS observation caught the emerging phase of the eclipse event. He emission lines in the spectra? say more here.

(2) SDSS J081708.16+340418.4 has a SDSS spectra which shows broad H Balmer absorption lines and confirms it as a white dwarf. The spectra doesn't show significant signal of double-peaked emission lines. If this is a detached binary system, the orbital radius is larger than the Roche radius. SDSS observation caught the emerging phase of the eclipse event. we can't determine the eclipse duration. The lower limit of the eclipse duration is about 5 minutes.

(3) SDSS J073827.00+150626.3 has no spectra or pre-

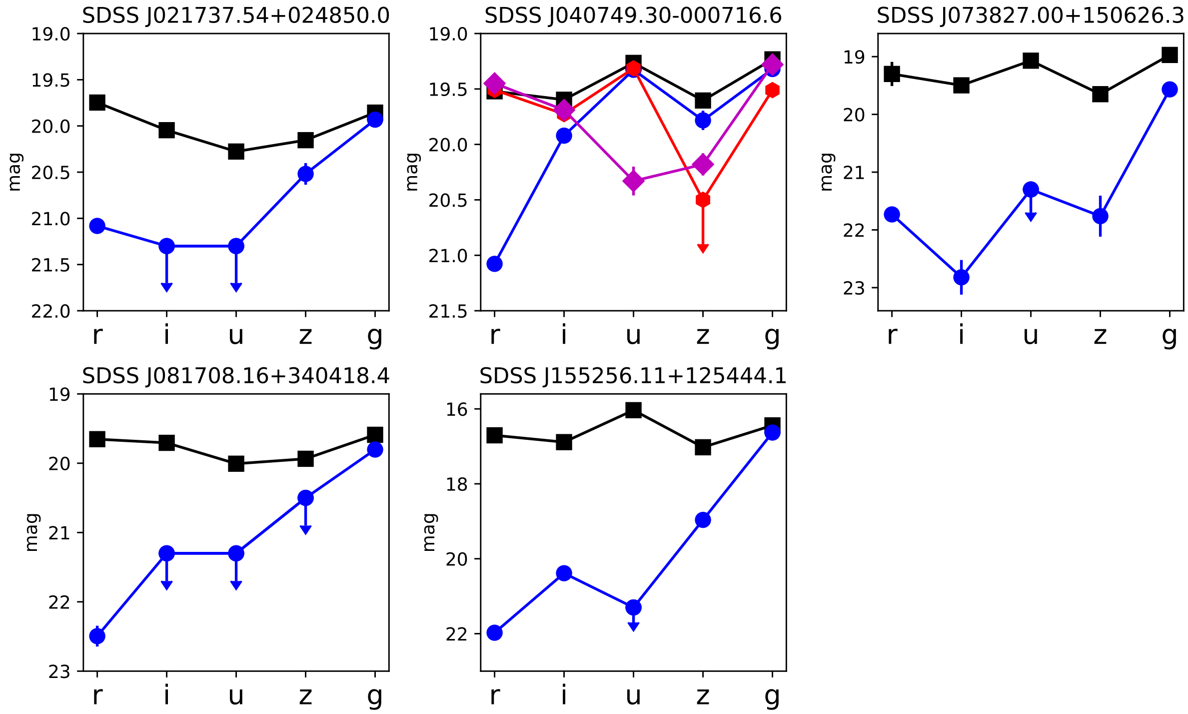

Figure 1. The light curves of five white dwarf eclipsing / transiting systems. The SDSS scan is in a sequence of r-i-u-z-g with 71.72 seconds scan time in each band. In each panel, the black squares show the referencing photometries. The blue dots (red hexagon and magenta diamond in panel 2) show the observations in which eclipsing / transiting events were detected. The downward arrows indicate non-detection in the corresponding bands. The differences between the reference and the new observation indicate the eclipsing fractions.

vious studies. It is dimmer by > 2.5 magnitudes during eclipses which have timescale of about five minutes. Any sign of companion star in the UV to NIR SED?

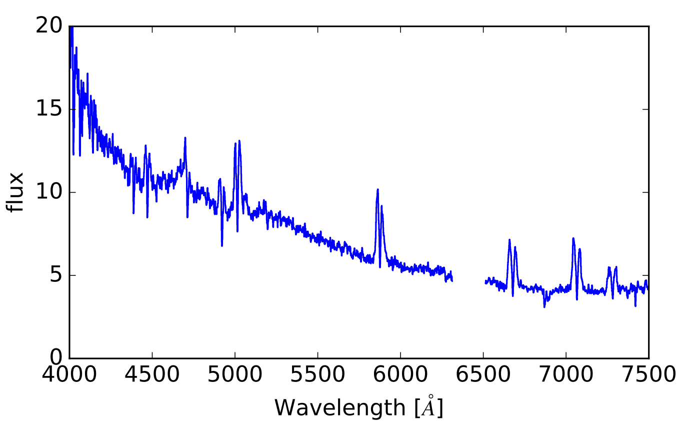

Figure 2. Optical spectra of SDSS J040749.30-000716.6 shows strong double-peaked HeI absorption lines. This object is among the very few eclipsing AM CVn systems.

3.1. *An eclipsing AM CVn system with eclipse duration of 1 minute*

SDSS J040749.30-000716.6 has 20 good SDSS observations. The eclipse event was detected in three SDSS observations (figure 1). The eclipse duration is about 1 minute. On 2018 Aug 18, we took optical spectra of this object with IMACS on Magellan 6.5m telescope. The spectra shows strong double-peaked HeI absorption lines (figure 2), indicating it is an AM CVn system. Our imaging follow-up shows it has an orbital period of 35 minutes. This object is among the very few eclipsing AM CVn systems in which the mass and radius of the binary can be accurately measured (e.g. Gaia14aae, Green et al. 2018). A detailed follow-up study is underway.

3.2. *An eclipsing system with eclipse duration of 5 minutes*

SDSS J021737.54+024850.0 has three SDSS observations. The eclipse event was detected in one SDSS observation during which the object disappeared in i and u bands images, indicating an eclipse duration of about 5 minutes.

We took follow-up photometry and spectroscopy observations. On 2018 Jan 20, we took a series of $Sloan-r$

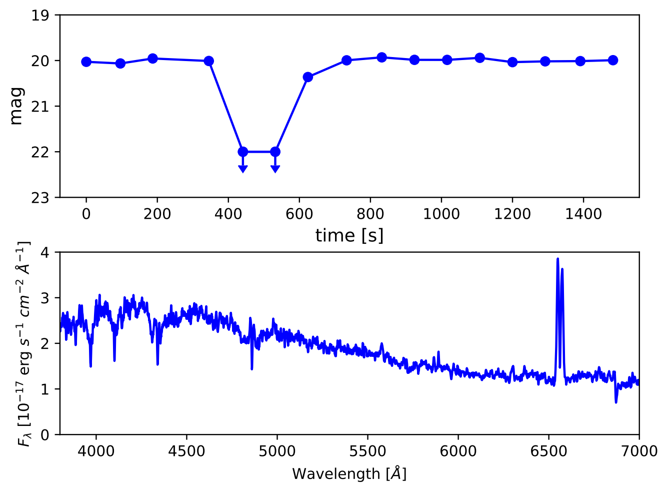

Figure 3. Light curve and spectra of SDSS J021737.54+024850.0. Top panel: r band light curve from the Du Pont observation shows an eclipse duration of about 4-5 minutes. Each point is a duration of 90 seconds. Bottom panel: optical spectra show double-peaked H Balmer emission lines, indicating the white dwarf is accreting from its companion.

band images for one houre with the CCD camera on the DuPont 2.5 meters telescope. We detected the eclipse event once (figure 3). The object is more than 2 magnitudes fainter during eclipse. On 2018 Jan 22, we observed this object with the Swope 1 meter telescope for 1.4 hours. Again, we detected the eclipse event once. The orbital period of the binary is between 1.4 to 48 hours, and probably a few hours based on Poisson probability.

On 2018 Jan 03, we took optical spectra of this object with MAGE on Magellan 6.5m telescope. The spectra shows broad H Balmer absorption lines and double-peaked H Balmer emission lines on top of the absorption lines. Its broadband photometries are consistent with a white dwarf with effective temperature of 9500 K and there is no strong signal of the companion. Therefore this is likely a system in which the white dwarf is accreting from a late-type M-dwarf or brown dwarf.

Assuming the white dwarf has mass of 0.6 $M_\odot$ and radius of $R_{WD} = 0.012R_\odot$, the minimum orbital period of 1.4 hours corresponds to a maximum orbital velocity of v = 463km s^{-1}. Because the transit duration is t = 300s, the maximum radius of the companion is $v \times t$ - R_{WD} = 20 R_{Earth}.

4. CONSTRAINTS ON PLANET AROUND WHITE DWARF

With this search, we can constrain the occurrence of planets around white dwarfs. Because SDSS observed a large sample of white dwarfs with short exposure time, it is mostly sensitive to planets close to the white dwarf. The expected number of planets, N_{exp}, can be calculated as

$$N_{exp} = N_{WD} \times p_{planet} \times p_{transit} \times p_{det}$$

, where N_{WD} is the number of observed white dwarf, p_{planet} is the probability to find a planet around a white dwarf, p_{planet} is the transit probability given a planet, and p_{det} is the detection efficiency, i.e. the probability to detect a transit event in a survey given a transit planet system.

In our search, we have 60,406 Gaia selected white dwarfs. The contamination is about 4 percent. Therefore the sample size N_{wd} is about 58,000. The transit probability is fully constrained by the geometry and equals $p_{transit} = (R_{planet}+R_{WD})/a$, where R_{planet} is the planet radius, R_{WD} is the white dwarf radius, and a is the orbital radius. Because we require a transit signal of at least 1 magnitude, only the transit system with obscuration fraction > 60% can be detected. This means we are not sensitive to planet with radius smaller than the WD radius. Here we use a simple approximation: the probability of a transit with large signal equals R_{planet}/a.

The detection efficiency depends on the parameter of the planet-WD system, the survey design, and the data analysis. For simplicity, we assume a central white dwarf mass of 0.6 M_{odot} and radius 0.012 R_{odot} (to be consistent with the previous studies in Fulton et al. 2014 and Sluijs et al. 2017). On average each WD was observed for about T_{obs} = 10 minutes by SDSS. The probability to catch the transit equals $(T_{obs} + T_{transit})/T_{orbit}$, where $T_{transit}$ is the transit duration and T_{orbit} is the orbital period.

In figure 4, we show the expected number of planets in our survey for different planet radius and orbital radius. Our search is most sensitive to planets around / outside the Roche limits. Because we don't know the probability of planet around white dwarf, we assume p_{planet} is 10% for all configurations (orbit, planet size, etc.) of the planet system. We expect to detect 3 -10 such objects. Because of the non-detection, the probability to find such object around a white dwarf is smaller than 10%.

costraints on AM CVn??

comparison to other searches

figure 6: number of white dwarfs vs. number of observations,

gaia 5s cadence. gaia will put a stronger limit soon.

5. CONCLUSION

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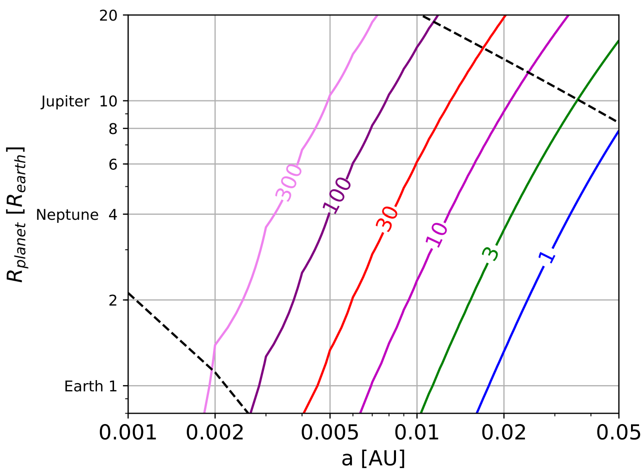

Figure 4. Effective number of white dwarfs. The lower bound and upper bound of the grey shade region corresponds to transit duration of 0.5 and 10 minutes.

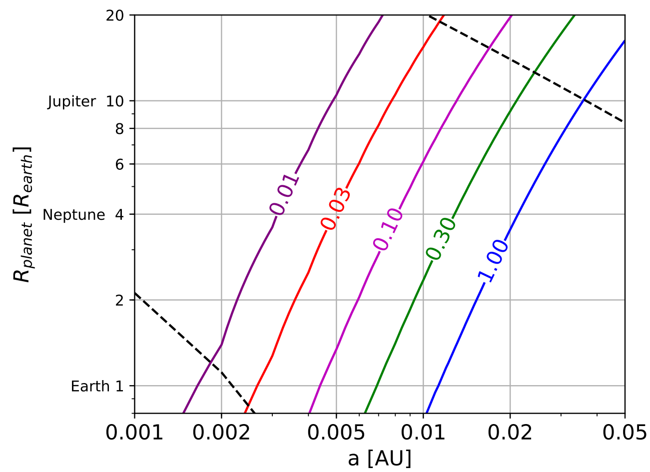

Figure 5. Limits on the probability of planets. The lower bound and upper bound of the grey shade region corresponds to transit duration of 0.5 minute and 10 minutes.

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