Publication Year	2020
Acceptance in OA	2022-03-29T14:37:35Z
Title	Detection and characterization of stellar magnetic activity with Gaia
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Publisher's version (DOI)	10.1002/asna.202013732
Handle	http://hdl.handle.net/20.500.12386/32057
Journal	ASTRONOMISCHE NACHRICHTEN
Volume	341

Received ; | Revised ; | Accepted
DOI: xxx/xxxx

ARTICLE TYPE

Detection and characterization of stellar magnetic activity with Gaia

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The Gaia Data Release 2 (DR2) supplied a catalogue of 147644 late-type stars for which the analysis of the G-band photometric time-series allowed the detection of the rotation period and an estimate of the magnetic activity level. The Gaia DR3 will be based on photometric time-series spanning a longer time interval and will allow the detection and the characterization of about 1 million stars with magnetic activity. In the present work we show how the Gaia data permit to study variability phenomena connected to the stellar magnetic activity and occurring on very different time scales. We also show how the Gaia data, combined with long-term photometric surveys like ASAS, can be exploited to detect magnetic activity cycles.

KEYWORDS:
stars:magnetic fields, stars:rotation, stars:flare, surveys

1 | THE STUDY OF STELLAR MAGNETIC ACTIVITY BY MEANS OF SPACE-BORN SURVEYS

Main Sequence stars with a type later than F5 and T-Tauri stars are characterized by a magnetic activity that is responsible for variability phenomena taking place on different time-scales. The optical flux coming from these stars can abruptly increase because of flaring events during which the stellar magnetic field undergoes to reconnection phenomena (see .e.g. Benz & Güdel, 2010; Shibata, 1999, for a description of these mechanisms). A typical flare event is characterized by a very fast flux rise (occurring on a few minutes) followed by a decay phase taking place on intervals ranging between 20 minutes to 6 hours (see e.g. Davenport, 2016; Doyle, Ramsay, Doyle, & Wu, 2019; Walkowicz et al., 2011). On a longer time-scale, the flux of magnetic active stars exhibits a periodic variation due to the stellar rotation that modulates the visibility of magnetic active regions unevenly distributed over the stellar disk. The time scale of these periodic variations is given by the stellar rotation period and can range between few hours to tens of days (see e.g. Lanzafame et al., 2018; McQuillan, Mazeh, & Aigrain, 2014). Finally, these stars are also characterized by variability phenomena taking place on several years that reflect changes in the morphology and in the intensity of the stellar magnetic field (like those occurring in the 11-yr solar cycle) (see e.g. Distefano, Lanzafame, Lanza, Messina, & Spada, 2017; Oláh et al., 2016, and reference therein). Ideally, the full characterization of variability phenomena in magnetic active stars would require long term (of the order of years) photometric time-series with a sampling shorter than the typical timescale of stellar rotation and flares duration. Unfortunately an all-sky photometric survey with these properties would be very time-consuming and does not exist. The CoRoT satellite (Convection, Rotation and planetary Transits Auvergne et al., 2009), launched in 2006 to search for rocky planets around nearby stars, was the first space instrument dedicated to the photometric monitoring of thousands of solar-like stars. The time-series collected by CoRoT, in three different optical bands, cover an interval of 150 d and are sampled at a cadence of 512 s for the most of its targets and at a cadence of 32 s for some selected targets. Hence these time-series are well suited to trace rotational modulation (see e.g. Affer, Micela, Favata, Flaccomio, & Bouvier, 2013) and to detect flare events (Flaccomio et al., 2018) but cannot supply information on long-term variability associated with magnetic cycles. The Kepler mission (Borucki et al., 2010) is characterized by 4 years long photometric time-series collected in two different cadences of 1 minute and 30 minutes, respectively. This survey permitted to analyze in detail the variations induced by rotational modulation in the stellar light curves of about 150000 late-type main-sequence stars and to study the flare occurrence in these stars (see e.g. McQuillan et al., 2014; Reinhold, Reiners, & Basri, 2013; Walkowicz et al., 2011). This mission allowed also the detection of magnetic cycles in about 3000 stars (Reinhold, Cameron, & Gizon, 2017). The limitation of this survey is that the field of view covers only a small sky region of 116 square degrees. The Tess mission (Ricker et al., 2015) is an all-sky survey and collects photometric observations with a two-minute cadenceThis cadence permits to study the time evolution of flare events with great detail (see e.g. Günther et al., 2020; Vida et al., 2019) But the most part of the target stars will be monitored for 27-d intervals. This implies that Tess data could not be used to measure rotation periods longer than $\simeq 15d$ and to study long term variability. The ongoing Gaia (Gaia Collaboration et al., 2016) mission over-come the Tess and Kepler limitations. Indeed, it is an all-sky survey but, at the same time, it will monitor each of its target stars for about 7 years, allowing the study of long- term variability. On the other hand, the Gaia time-series have a very sparse sampling that does not permit to trace in detail the shape of the stellar light curves or to study the time evolution of flare events. However, as we'll show in the next section, the Gaia sampling is good enough, at least at certain coordinates, to allow the recovery of the stellar rotation periods and the detection of flare events. Finally, Gaia is better suited to characterize the variability of stars falling in crowded fields because of its fine point-spread function. In fact, the spatial resolution of its telescopes is about 0.23 $arcsec$ in the along-scan direction and 0.70 $arcsec$ in the across-scan direction, whereas the Kepler and Tess PSF are of several $arcsec$. The high spatial resolution makes Gaia photometric time-series poor affected by contamination of nearby sources that could dilute the variability of the target star or, in the worst cases, add spurious variability. In the second section of this paper we illustrate the main properties of the Gaia mission and of the pipeline designed to characterize magnetic active stars with the use of Gaia data. In the third section we analyze in detail the Gaia photometric time-series for the star Gaia DR2 2925085041699059712. This star is a magnetic active star detected for the first time by the Gaia mission. In the fourth section we show how the combination between Gaia and the ASAS(Pojmański, 2001) survey can be exploited to detect long-term (with years duration) magnetic cycles.

2 | THE GAIA MISSION AND THE CHARACTERIZATION OF MAGNETICALLY ACTIVE STARS.

The Gaia mission is an all-sky-survey with the aim to observe about 1 billion sources down to the limit magnitude G$\simeq$ 20 and to collect photometric time-series in the three photometric bands G, G_{BP} and G_{RP}. The time-series are collected by two different telescopes separated by a 106 deg angle and rotating around a spin axis that forms a 50 deg angle with the Sun-Gaia direction. Because of this rotational motion the fields of view of the two telescopes are named Preceding Field of View (PFOV) and Following Field of View (FFOV). The sampling of the photometric time-series collected by Gaia is not regular and changes with the coordinates of the target star according to the satellite scanning law. The Gaia scanning law is determined by the combination of three motions that are the 6-hours rotation of the satellite, the 63-days precession motion of the spin axis around the Gaia-Sun direction and finally the 365-d revolution around the Sun. As a result of these three motions, a typical Gaia time-series is characterized by "groups" of observations closely spaced in time. The typical gap between two consecutive groups is about 60-d for stars placed at ecliptic latitudes $-30\,\text{deg} \leq \beta \leq 30\,\text{deg}$ and about 36-d in other directions. The number of observations per group is in turn a complicated function of the star coordinates. At ecliptic latitudes $\beta \leq -45\,\text{deg}$ and $\beta \geq 45\,\text{deg}$, a group is made of two observations. At ecliptic latitudes $-45\,\text{deg} \leq \beta \leq 45\,\text{deg}$ the number of observations per group range between 2 and 60. In a given group the interval between two consecutive observations can be 1.22 h, 4.78 h and 6 h where the first interval corresponds to a transition of the target stars from the PFOV to the FFOV, the second to a transition from the FFOV to the PFOV and the third to a complete rotation of the satellite (see Distefano et al., 2012; Eyer & Mignard, 2005, for a detailed description of the Gaia sampling features). Distefano et al. (2012) simulated thousands of light curves of magnetically active stars sampled as the Gaia time-series and studied how the sampling can affect the recovery of the stellar rotation period. They found that the Gaia scanning law favors the detection of rotation periods shorter than $5d$ and that the rate of correct detections is very high at ecliptic latitudes close to $\beta \pm 45\,\text{deg}$ where groups of 30-40 observations are collected (see e.g. Fig. 2). The Gaia DR2 has supplied a catalogue of 147644 solar-like stars i.e. stars whose variability is due to magnetic phenomena similar to those occurring in the Sun. The pipeline used by the Gaia DPAC (Data Process and Analysis Consortium) to detect and characterize these stars is described in detail in Lanzafame et al. (2018) and Eyer et al. (2018). Briefly, this pipeline selects solar-like star candidates by looking at their location in the Gaia HR diagram and then analyzes their photometric time-series with the aim to recover their rotation period and to measure their magnetic activity level. Each time-series is segmented in intervals not exceeding 120 d and the generalized Lomb-Scargle algorithm is run on each segment. If the same period is recovered in at least two segments, the star is flagged as a solar-like star. The DR2 catalogue reports, for each segment, the detected rotation period and the magnetic activity index A.I. that is defined as

$$A.I. = G_{95th} - G_{5th} \tag{1}$$

where G_{95th} and G_{5th} are the 95-th and 5-th percentile of G mag measurements in the segment, respectively. The catalogue also reports, for each star, the best estimate of the rotation period. More details on the contents of this catalogue can be found in Lanzafame et al. (2018). In the following sections we show how the Gaia data can be used not only to characterize the variability due to rotational modulation but also to characterize variability phenomena occurring in shorter and longer time-scales.

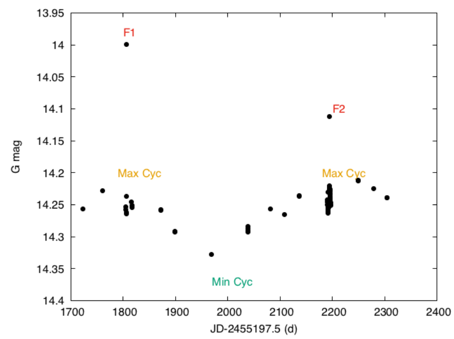

FIGURE 1 G photometric time-series of Gaia DR2 2925085041699059712. A long term variability likely due to 500-d magnetic cycle is clearly visible. Two flare candidates are flagged with label F1 and F2, respectively.

3 | GAIA DR2 2925085041699059712

The star Gaia DR2 2925085041699059712 with magnitude G = 14.2 and $T_{\rm eff} = 4791.65K$ is a late type star whose rotation period $P_{\rm rot} = 6 \pm 0.7d$ was measured for the first time by the Gaia pipeline deputed to the analysis of solar-like stars (Lanzafame et al., 2018). The visual inspection of the G photometric time-series released in Gaia DR2 shows that, in this star, the variability due to rotational modulation is superimposed on a long-term variability due to a possible magnetic cycle with a $\simeq 500d$ duration. The photometric time-series exhibits also some outliers that could be ascribed to a flaring activity. In Fig. 1 we show the full photometric time-series. The 500 d activity cycles is clearly visible and two points labelled ad F1 and F2 are candidate flare events. In Fig. 2 we show a sequence of about 40 G mag measurements closely spaced in time acquired during a 9 days long time interval. This observations sequence permits to sample a complete stellar rotation and makes the detection of the rotation period very easy. This kind of sequences can occur, as remarked in the above section, at ecliptic latitudes close to $\beta = \pm 45$ deg and make Gaia time-series very suitable to characterize stars with a short rotation period. In Fig. 2 a third outlier, labelled as F3, could be another flare event less energetic than F1 and F2.

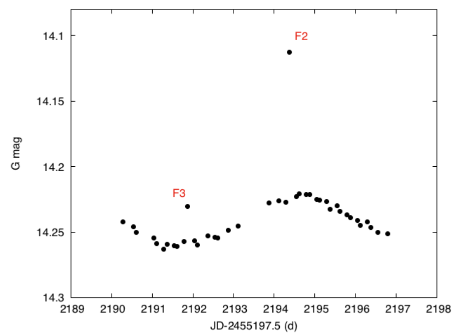

FIGURE 2 G photometric observations of Gaia DR2 2925085041699059712 collected during a 9-d time interval. A third flare candidate is flagged with label F3.

4 | GAIA DR2 3246069594362282752

The source Gaia DR2 3246069594362282752 is a magnetically active star known also as TYC 4723-976-1 or ASAS J034922-0514.3. The rotation period of this star was measured for the first time by Kiraga (2012) who analyzed the ASAS photometric time-series for a set of stars listed in the ROSAT All Sky Survey Bright Source Catalog (RSBC) and, therefore, characterized by a strong X-Ray chromospheric emission. Kiraga (2012) found a period $P = 0.593d$ that is in good agreement with the period $P_{\rm rot} = 0.59 \pm 0.005d$ reported in the Gaia DR2 catalogue of variable stars with rotational modulation. The ASAS photometric time-series was collected in the Jonson V photometric band and span an interval of about 9 years. We converted the Gaia photometric measurements acquired in the G band into the Jonson V photometric band by means of the equations supplied by Evans et al. (2018) and we merged the two photometric time-series. In this way we obtained a photometric time-series spanning about 15 yrs. We

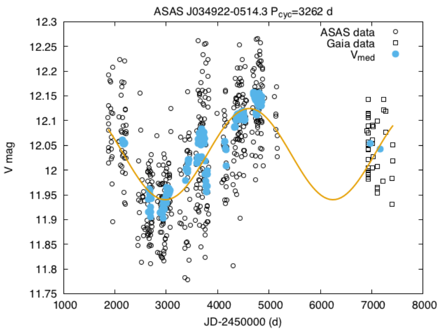

FIGURE 3 Black empty bullets: ASAS V mag time-series for the source ASAS J034922-0514.3. Black empty squares: Gaia observations converted into the photometric V band. Cyan bullets: median magnitudes in 50-d segments.

processed this photometric time-series and searched for a magnetic cycle by adopting the same strategy used in Distefano et al. (2017) . Briefly, we segmented the whole time-series with a 50-d sliding window and we computed, in each segment, the median magnitude *V* med. This parameter can be regarded as an indicator of the stellar magnetic activity because it is related to the axisymmetric part of the spot distribution on the stellar surface (see e.g. Lehtinen, Jetsu, Hackman, Kajatkari, & Henry, 2016; Rodonò, Messina, Lanza, Cutispoto, & Teriaca, 2000) We run the Lomb-Scargle algorithm on the $V_{\rm med}$ time-series and we found a significative peak in the periodogram at $P_{\rm cyc} = 3262 \pm 125d$ (see Distefano et al., 2017, for details on how the peak significance is assessed). In Fig. 3 we reported the whole photometric time-series. The empty bullets mark the ASAS observations whereas the empty squares mark the Gaia measurements converted into the Jonson V band. The cyan bullets are used to plot the $V_{\rm med}$ time-series. The sinusoid best-fitting the data is over-plotted on the time-series.

5 | CONCLUSIONS

In this work we showed how the Gaia data can be exploited to analyze variability phenomena due to magnetic activity on different time-scales. The Gaia mission can complement the information coming from Tess and Kepler to better characterize the stars with magnetic activity phenomena. In fact, Tess could only supply the rotation period for the most of its targeted stars whereas Gaia could provide information on long-term variability due to magnetic cycles. Gaia data, spanning a 7 years intervals, could be exploited also to study how the detected rotation period changes in time and to reveal differential rotation by using the same strategy adopted in Distefano, Lanzafame, Lanza, Messina, & Spada (2016). Kepler data were also exploited to study magnetic cycles and differential rotation in a wide sample of stars. But these studies concern only the Kepler field of view of 116 square degrees, whereas Gaia will permit to study these properties in different regions of our galaxy and open clusters and to connect these properties with the stellar ages. Finally, Gaia will also permit the detection of flare events. Unfortunately, the Gaia sampling does not permit to characterize the time-evolution of the flare because, in the most favorable case, the interval between two consecutive observations is about 1.78 h that is longer than the typical time-scales of flare evolution. Nevertheless Gaia will permit to make a lower estimate for the energy released in these events and will register also the spectra associated with these events that could give valuable information on our understanding of these phenomena.

ACKNOWLEDGMENTS

The extensive use of the SIMBAD and ADS databases operated by the CDS centre, Strasbourg, France, is gratefully acknowledged. The Authors would like to thank Dr. G. Pojmanski for the use we made of the ASAS database.

Financial disclosure

None reported.

Conflict of interest

The authors declare no potential conflict of interests.

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How cite this article: E. Distefano, and A. Lanzafame, (2019), Detection and characterization of stellar magnetic activity with Gaia, *A.N.*, .

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