Predictions of Astrometric Jitter for Sun-like Stars. I. The Model and Its Application to the Sun as Seen from the Ecliptic

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Abstract

The advent of Gaia, capable of measuring stellar wobbles caused by orbiting planets, raised interest in the astrometric detection of exoplanets. Another source of such wobbles (often also called jitter) is stellar magnetic activity. A quantitative assessment of the stellar astrometric jitter is important for a more reliable astrometric detection and characterization of exoplanets. We calculate the displacement of the solar photocenter due to the magnetic activity for an almost 16 yr period (1999 February 2–2014 August 1). We also investigate how the dependence varies on the spectral passband chosen for observations, including the wavelength range to be covered by the upcoming Small-JASMINE mission of JAXA. This is done by extending the SATIRE-S model for solar irradiance variability to calculating the displacement of the solar photocenter caused by the magnetic features on the surface of the Sun. We found that the peak-to-peak amplitude of the solar photocenter displacement would reach 0.5 \( \mu \)as if the Sun were located 10 pc away from the observer and observed in the Gaia G filter. This is by far too small to be detected by the Gaia mission. However, the Sun is a relatively inactive star so one can expect significantly larger signals for younger, and, consequently, more active stars. The model developed in this study can be combined with the simulations of emergence and surface transport of magnetic flux which have recently become available to model the astrometric jitter over the broad range of magnetic activities.

Unified Astronomy Thesaurus concepts: Stellar activity (1580); Solar activity (1475); Astrometric exoplanet detection (2130); Stellar atmospheres (1584)

1. Introduction

The discovery of an exoplanet rotating around a main-sequence star (Mayor & Queloz 1995) initiated the new, highly dynamical field of exoplanetary science. As of today, more than 4000 planets have been confirmed.3 Presently the main techniques for discovering exoplanets are transit photometry and radial velocity (RV) measurements. In particular, there have been no reliable astrometric detections until now. However, it is expected that the situation will soon change due to the advent of ultra-precise astrometry. For example, it has been estimated (Perryman et al. 2014) that astrometric measurements by the Gaia mission (Gaia Collaboration 2016) would lead to a discovery of more than 20,000 exoplanets. The main idea behind the astrometric approach is to detect the displacement of the stellar photocenter caused by the rotation of a star around star–planet barycentre. Interestingly, apart from the exoplanets, the stellar photocenter can also be displaced by the magnetic activity of a star, since bright and dark magnetic features on a stellar surface affect the position of the photocenter (see, e.g., Lanza et al. 2008). We note that the activity-induced astrometric and photometric signals have common origin. A dark spot on the stellar disk not only reduces stellar brightness but also repels the stellar photocenter, e.g., a spot at the western part of the stellar disk will shift the photocenter to the eastern part. Likewise, a bright facular region increases stellar brightness and attracts the photocenter. Consequently, similarly to the case of photometric and RV measurements the intrinsic astrometric jitter from the host stars might become a hurdle for detecting and characterizing exoplanets with astrometry.

3 http://exoplanet.eu/catalog

A significant effort (see, e.g., Eriksson & Lindegren 2007; Catanzarite et al. 2008, and references therein) has been invested in modeling such an astrometric jitter in anticipation of the planned (but never realized) Space Interferometry Mission. In particular, Makarov et al. (2009) developed an analytical model attributing photometric, astrometric, and RV jitter to a single spot on the stellar surface. They estimated that the solar jitter can reach a value of 1.5 \( \mu \)au. Makarov et al. (2010) used Mount Wilson magnetograms and intensity images to create disk maps of solar bolometric surface intensity and to directly calculate the position of the solar photocenter. They found that largest deviation reaches 2.6 \( \mu \)au and the standard deviation of the solar photocenter in the year 2000 was 0.91 \( \mu \)au. A similar result was later obtained by Lagrange et al. (2011), who used a more comprehensive model, developed by Meunier et al. (2010), and MDI/SOHO magnetograms to conclude that the solar astrometric jitter is most of the time smaller than 2 \( \mu \)au. Recently, Meunier et al. (2019) outlined how to extend these calculations to other Sun-like stars.

Lately, the motivation to model astrometric jitter has been boosted by data from the Gaia mission (e.g., astrometric data from the first 22 months of observations have been recently released, see Lindegren et al. 2018). For example, Morris et al. (2018) constructed a model attributing solar and stellar astrometric jitter to dark spots (i.e., neglecting contributions from bright faculae) and found that the precision of Gaia should be sufficient to detect astrometric jitter in the nearest active stars.

Concurrently with studies of the stellar jitter, a number of models of solar irradiance variability have been created (see, e.g., Ermolli et al. 2013; Solanki et al. 2013, for reviews). The main motivation for the development of such models came from a suspected link between the solar irradiance variability...
and the natural climate change (see, e.g., review by Gray et al. 2010, and references therein). Later, some of these solar models, in particular the Spectral And Total Irradiance Reconstruction (SATIRE Fligge et al. 2000; Krivova et al. 2003) model, were successfully applied to the analysis and explanation of the photometric data from Sun-like stars (e.g., Shapiro et al. 2014; Karoff et al. 2018; Witzke et al. 2018; Reinhold et al. 2019).

In this paper, we take a first step in applying the solar paradigm to calculating astrometric jitter from Sun-like stars. To that end, we extend the SATIRE model to calculating the astrometric jitter produced by the Sun. In particular, we have calculated solar astrometric jitter as it would be seen by the Gaia and Small-JASMINE mission, which is a JAXA space mission for monitoring the distances and motions of stars in the near-infrared (planned to be launched in 2024, see Utsunomiya et al. 2014). However, before utilizing the full power of the SATIRE approach we present a simple and more straightforward estimate of the astrometric jitter in Section 2.

2. Single-spot Estimate

The main goal of this section is to provide a very simplified estimate of the amplitude of the astrometric jitter, which can be expected for Sun-like stars before indulging in developing a much more realistic (and also sophisticated) model. Namely, we connect here the amplitudes of the stellar astrometric jitter and brightness variability assuming that both phenomena are attributed to the periodic transits of a not-evolving single spot over the visible stellar disk as the star rotates. We note that such an assumption is not expected to accurately represent the solar case. Indeed, the variability of the Sun is brought about by multiple spot and facular features whose distribution on the solar surface is rather intricate (see, e.g., Solanki et al. 2006). A single-spot estimate might also be oversimplified for calculating the astrometric jitter of young cool stars since it was suggested that some of them have a large number of spots on their surfaces (Jackson & Jeffries 2012). At the same time Işık et al. (2020) recently proposed that the variability of highly variable stars with near-solar fundamental parameters and rotation periods (see Reinhold et al. 2020; Zhang et al. 2020) could be explained by the strong degree of nesting of magnetic features on their surfaces. Such highly nested distributions of magnetic features could be much better approximated by a single-spot model than that of the Sun (see, e.g., Figure 2 from Işık et al. 2020).

We consider a case of a star observed from its equatorial plane and a spot located in the stellar equator. Let us further assume that brightness contrast of the spot with respect to the quiet stellar regions does not depend on the position of the spot on the stellar disk (which is a reasonable simplification, see, e.g., Figure 4 from Shapiro et al. 2014). In such a case the relative drop of the stellar brightness due to the spot located on the visible disk can be written as $\Delta \cos \phi$, where $\Delta$ is a drop of the brightness when the spot is located in the visible disk center and $\phi$ is the heliocentric angle of the spot (so that $\cos \phi$ represents foreshortening, i.e., it is equal to 1 for the spot located in the center of the visible disk and 0 for the spot located at the limb). At the same time the shift of the photocenter can be written as $R \cdot \Delta \cos \phi \sin \phi$, where $R$ is the visible angular radius of the star. Consequently, the maximum shift of the photocenter from the stellar disk center corresponds to $\phi = \pi / 4$ and it is equal to $R \cdot \Delta / 2$. The trajectory of the photocenter is a straight line with stellar disk center located in the middle of this line so that the peak-to-peak amplitude of the photocenter’s displacement is twice this value.

The angular radius of a star with solar radius located at 10 pc from the observer is ca. 500 $\mu$as. We can now connect the amplitude of the brightness variations, $A_{\text{brightness}}$, and astrometric jitter, $A_{\text{jitter}}$, for such a star:

$$A_{\text{jitter}} [\mu\text{as}] = 5 \cdot A_{\text{brightness}} [\%].$$

Over the last 40 yr there have been several episodes when the transit of a large sunspot group caused a drop of the solar brightness by 0.2–0.3% (see, e.g., Figure 2 from Kopp 2016). Equation (1) then points to the amplitude of the astrometric jitter of 1–1.5 $\mu$as. Since such episodes of high variability are rather rare, a more robust measure of solar and stellar rotational brightness variability might be the $R_{\text{var}}$ metric introduced by Basri et al. (2010, 2011) for quantifying stellar brightness variations observed by the Kepler telescope. To calculate $R_{\text{var}}$ first the peak-to-peak (or more precisely relative difference between the 95th and 5th percentile of the sorted flux values) variability in each of the 90 days Kepler quarters is calculated and then the median value among all quarters is taken. The total duration of Kepler observations is about 4 yr, so that $R_{\text{var}}$ value corresponds to the mean variability over this period. By “keplerizing” available solar data (see, e.g., Basri et al. 2013), Reinhold et al. (2020) showed that the mean value of the solar $R_{\text{var}}$ over the last 140 yr is 0.07%, while the maximum value is 0.18%. These numbers transfer to 0.35 and 0.9 $\mu$as amplitudes of the displacement, respectively. At the same time, Reinhold et al. (2020) showed that $R_{\text{var}}$ values for stars with near-solar fundamental parameters and rotation periods can reach up to 0.7%, which would correspond to a displacement value of 3.5 $\mu$as. The $R_{\text{var}}$ values of faster rotating G-dwarfs can reach up to 3% (see, Figure 4 from McQuillan et al. 2014) corresponding to a displacement of 15 $\mu$as.

The along-scan single-epoch precision of the Gaia measurements for the brightest stars is about 34 $\mu$as (although a more optimistic value of 11 $\mu$as has also been used in the literature, see Perryman et al. 2014, for a discussion). Consequently, our simple estimate shows that if the Sun were observed by Gaia from a distance of 10 pc, its activity would be too low to affect the measurements. At the same time, our estimate shows that the astrometric jitter might become an important factor for more active stars, especially since Gaia performs multiple measurements of the same stars (with their number reaching up to ca. 100 for stars at intermediate galactic latitudes (Perryman et al. 2014).

In the next sections of this paper we present much more accurate calculations of solar astrometric jitter based on the observed distribution of solar magnetic features and the SATIRE model. We expect that jitter returned by this model would reflect the jitter from other Sun-like stars with a similar activity level (if observed roughly equator-on). In subsequent publications we will present an extension to calculating astrometric jitter for stars with different fundamental parameters and with a broad range of magnetic activity values and observed at random inclinations, i.e., angles between the direction to observer and rotation axis (see discussion in Section 5).
3. Model Description

We utilize a highly precise version of the model, SATIRE-S, based on the satellite measurements of the magnetic field distribution on the solar disk (Krivova et al. 2011). SATIRE-S irradiance time series have been demonstrated to be consistent with solar observations from multiple sources (see, e.g., Ball et al. 2014; Yeo et al. 2014, 2015; Danilovic et al. 2016, and references therein). The SATIRE-S model accounts for the irradiance variations brought about by magnetic features (namely bright faculae and dark sunspot umbrae and penumbrae) on the solar surface. It uses full-disk magnetograms and intensity images of the Sun taken with daily cadence to determine the coverage of the solar disk by magnetic features. The intensities of the quiet Sun and magnetic features have been calculated by Unruh et al. (1999) with the ATLAS9 code (Kurucz 1992; Castelli & Kurucz 1994).

3.1. Photometric Signal

The calculations of the solar irradiance at any given day are done in the following steps. First, fractional coverages of each pixel of the magnetogram by magnetic features and quiet Sun (i.e., regions of the solar surface covered by neither faculae, nor spots) are calculated (see Yeo et al. 2014, for details of the calculations). Second, for each magnetogram pixel the radiation from the region on the solar surface corresponding to this pixel is computed. This is done by summing up radiation values from the quiet Sun and magnetic features, weighted with corresponding fractional coverages of the pixel. Finally, the irradiance from the full solar disk is calculated by summing up the contributions from all pixels.

Let us now apply such an approach for calculating solar irradiance passing through a filter with a given passband. The ratio between the magnetic component of the irradiance and the irradiance from the full-disk quiet Sun (i.e., Sun free from any magnetic features) can be found with the following equation:

$$B(t) = \sum_i \sum_{k=0} \alpha_k^i(t) (F_k^i - F_0^i) \sum_i F_0^i.$$  \hspace{1cm} (2)

Here the first summation (over $i$) is done over all solar disk pixels. The second summation (over $k$) is done over the three classes of magnetic features considered in the SATIRE-S model, i.e., faculae, spot umbrae, and spot penumbrae (corresponding to $k = 1, 2, 3$, respectively). $\alpha_k^i(t)$ is the fractional coverage of the $i$th pixel by the $k$th component and $F_k^i$ is irradiance from the $i$th pixel fully covered by the $k$th component. $k = 0$ corresponds to the quiet solar regions.

The $F_k^i$ values can be written as

$$F_k^i = \Delta \Omega \int \lambda I(\lambda, \mu_i) \phi(\lambda) d\lambda,$$  \hspace{1cm} (3)

for detectors measuring energies (like all TSI instruments) and

$$F_k^i = \Delta \Omega \int \lambda I(\lambda, \mu_i) \phi(\lambda) / (hc/\lambda) d\lambda,$$  \hspace{1cm} (4)

for detectors counting photons (see, e.g., the discussion in Maxted 2018). $\Delta \Omega$ in Equations (3)–(4) is the solid angle of the region on the solar surface that corresponds to one pixel when the magnetograms are obtained at 1 au from the Sun. $\lambda$ is the intensity from the $k$th component. The intensities entering the SATIRE-S model can be written as a function of wavelength $\lambda$ and the cosine of the angle between the direction to the observer and the local stellar radius, $\mu_i$, corresponding to the $i$th pixel (neglecting the change of the cosine value within the pixel). Finally, $\phi(\lambda)$ is the transmission curve. We used Equation (4) for calculating solar astrometric and photometric signals as they would be measured by the photon-counting CCD detectors of Gaia and Small-JASMINE. Equation (3) was used for the TSI calculations. Naturally, the radiometers used for the TSI measurements (see, e.g., Kopp 2016) cannot be used for measuring stellar positions. Nevertheless, we also show astrometric signal as it would be measured in TSI to better illustrate its wavelength dependence.

3.2. Astrometric Signal

The shift of solar photocenter due to the magnetic activity can be found with an equation similar to Equation (2):

$$\begin{pmatrix} \bar{X} \\ \bar{Y} \end{pmatrix} = \sum_i \sum_{k=0} \alpha_k^i(t) \left[ \frac{X_i F_k^i - F_0^i}{(1 + B(t)) \sum_i F_0^i} \right].$$  \hspace{1cm} (5)

Here $\bar{X}$ and $\bar{Y}$ are shifts along and perpendicular to the equatorial plane, respectively. $X_i$ and $Y_i$ are the coordinates of the $i$th pixel. The origin of the coordinate system is chosen to coincide with the solar disk center.

In this study we calculate the trajectory of the solar photocenter with a daily cadence for the period from 1999 February 2 until 2014 August 1. The $\alpha_k^i$ values have been taken from Yeo et al. (2014) who determined them based on the data from the Michelson Doppler Imager on board the Solar and Heliospheric Observatory (SOHO/MDI, Scherrer et al. 1995) prior to 2010 April 30 and from the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory (SDO/HMI, Scherrer et al. 2012; Schou et al. 2012) for the subsequent period. A special homogenizing procedure has been applied to ensure the consistency between the two resulting segments of the reconstruction (see Yeo et al. 2014, for more details).

4. Results

To better illustrate the origin of the solar photocenter displacement we start with considering a case of the hypothetical transit of a single active region across the visible solar disk before moving to more sophisticated calculations of the displacements corresponding to the observed distribution of active regions. Namely, we consider the case of a relatively large active region (see, e.g., Baumann & Solanki 2005, for the size distribution of active regions) with a spot area of 3000 MSH (micro solar hemisphere) and a facular area of 9000 MSH (corresponding to 0.6% and 1.8% coverages of the visible solar disk when observed near the disk center, respectively). The ratio between the areas of the facular and spot parts of active region has been taken from Shapiro et al. (2020). Following Wenzler et al. (2006) the spot area of the active region was set to consist of 80% penumbra and 20% umbra. We have considered the non-evolving point-like (i.e., described by a single $\mu$ value) active region which transits the solar disk at the latitude of $30^\circ$.

Figure 1 presents the displacements of the solar photocenter relative to the solar disk center measured in milli solar radii ($mR_{\text{sun}}$) and radiative flux changes (measured in mmag) associated with such a transit. The displacements and
brightness changes are plotted versus the phase of the transit, which is, hereafter, defined as the longitude of the active region measured relative to the plane containing the observer and solar rotation axis. It equals \(-90^\circ\) when the active region just rotates in at the western limb, changes sign from minus to plus when the active region passes above the solar disk center, and it equals \(90^\circ\) when the active region disappears at the eastern limb. We show the displacement and radiative flux changes as they would be measured in the Gaia G passband, the Total Spectral Irradiance (TSI, i.e., spectrally integrated radiative flux), and Small-JASMINE passband. The spectral transmission of the Gaia G passband has been taken from the Gaia DR2 revised passbands webpage.\(^4\) The G passband covers the wavelengths between 330 and 1050 nm (Evans et al., 2018). The exact spectral transmission of the Small-JASMINE mission (Utsumomiyai et al., 2014) is not yet available but it is anticipated that Small-JASMINE will make measurements in the 1.1–1.7 μm spectral interval. We have, therefore, considered a rectangular spectral transmission profile returning unity within this spectral interval and zero outside of it.

We put the origin of the coordinate system into the center of the solar disk (which is assumed to be circular). The solar photocenter is located there before the active region rotates in. As soon as the active region appears at the western part of the solar disk its dark spot part starts to repel the photocenter while its bright facular part starts to attract it. This is illustrated by the color curves in Figure 1 which show how the trajectories of the solar photocenter would look if only the spot and facular part (blue and red curves, respectively) of the active region transited the solar disk. One can see that the transit of a spot would cause the photocenter to move clockwise in the loop trajectory at negative ordinates and lead to the increase of the solar brightness. The facular brightness contrast noticeably decreases when the facular region passes close to the disk center (i.e., when it corresponds to near-zero phase values, see Figure 1) leading to the decrease of the facular effect on the position of the photocenter and solar brightness. As a result, the transit of facular region leads to the heart-like shaped trajectory of the photocenter and two-peak profile of the brightness change. Such a decrease of the facular contrast is especially pronounced for the Small-JASMINE passband (see Figures 1(c), (f)) where it drops almost to zero when active region crosses \(Y\)-axis.

The net effect of the transit of the active region is given by the competition between spot and facular effects. Since brightness contrast of faculae strongly increases toward the limb, the facular effect overweights that of the spot when the active region is close to the limb. Consequently, after the active region rotates in at the western limb the photocenter first starts to move toward it, i.e., its abscissa gets negative while the ordinate gets positive. This is clearly visible in all three trajectories (black curves in Figures 1(a)–(c)), although since facular contrast is decreasing in the infrared (see also below) the initial shift toward the active region is relatively small for the Small-JASMINE.

By the same token the active region first leads to the increase of the solar brightness. As the active region rotates further from the limb the relative contribution of faculae becomes weaker and the solar photocenter starts to move back toward the disk center. The photocenter follows a very similar trajectory to what it made moving toward the active region, e.g., these back and forth trajectories are indistinguishable in Figure 1. After passing through the disk center the solar photocenter makes a loop trajectory with negative ordinates before starting to move toward the active region again (which happens when the active region gets close to the eastern limb). Likewise, the effect of the active region on solar brightness remains negative (i.e., active region decreases the brightness) most of the time before increasing closer to the end of the transit. Naturally, after the transit (i.e., when active region rotates out of the visible solar disk) the solar photocenter returns back to the disk center and the solar brightness becomes equal to that of the quiet Sun.

Figure 1 demonstrates that the largest displacements are observed in Gaia G passband, which appears to be more appropriate for detecting stellar jitter than TSI (i.e., white light). One can see that the partial compensation between spot and facular components noticeably decreases the amplitude of the displacements and brightness changes in the Gaia G passband and TSI. The compensation is particularly strong in the TSI leading to the net effect of the active region transit there being very similar to that in the Small-JASMINE passband (for both displacement of the photocenter and brightness change), despite individual spot and facular effects being significantly smaller in the Small-JASMINE passband. This is because spot and facular contrasts both decrease toward the infrared but the facular contrast decreases faster. Consequently, the displacement of the photocenter and brightness changes in the Small-JASMINE passband are mainly brought about by the spot part of the active region and the facular part has only a very small contribution to the photocenter displacement and brightness change.

Now we move to considering displacements caused by the observed distributions of magnetic features on the solar disk.

\(^4\) [www.cosmos.esa.int/web/gaia/iow_20180316](https://www.cosmos.esa.int/web/gaia/iow_20180316)
Figure 2. The daily (blue asterisks) and averaged over 81 days (red asterisks) displacements of the solar photocenter as they would be seen in the Gaia G passband for the period 1999 February 2–2014 August 1. Shown are total displacements (top panel), as well as their spot (middle panel) and facular (bottom panel) components. X- and Y-axes are chosen to be along and perpendicular to the solar equator, respectively, and have equal scaling to better illustrate the shape of the photocenter trajectory.

Figure 2 shows the displacements in the Gaia G passband over the whole period considered in this study. One can see that the clouds of points representing daily displacements (blue asterisks in Figure 2) are elongated along the solar equator (i.e., along the X-axis). This is because solar magnetic features are mainly concentrated in the low latitude regions of the Sun. For example, large spots rarely appear at latitudes higher than 30° and large facular regions are mainly concentrated at latitudes below 40°.

The displacements along the equator almost fully average out when 81 days averaging is applied (red symbols in Figure 2). This is because the activity in the western and eastern hemispheres of the Sun is on average the same. A larger averaged displacement remains along the Y-axis, which is caused by the 7°25 angle between the solar equator and ecliptic and the resulting apparent asymmetry of active region distributions along the Y-axis. We note that due to the Earth’s orbit around the Sun, the solar inclination (i.e., the angle between the rotation axis and direction to the observer) oscillates between 82°75 (in September and March) and 90° (in December and June). Consequently, the solar photocenter oscillated with an annual period which is just a feature of the Sun observed from the vantage point of the Earth. Such an oscillation will not be present in observations of other stars (see also discussion in Makarov et al. 2009).

The middle and bottom panels of Figure 2 present displacements of the solar photocenter brought about by spots and facular features alone. One can see that, while the facular component of the displacement is relatively small and rather compact, the spot component has a number of larger excursions caused by transits of large spot groups. Since spot groups are accompanied by facular features which partly compensate displacements brought about by spots the excursions are more pronounced in the spot component than in the total displacement.

In Figure 3 we plot the trajectory of the solar photocenter during the period from 2003 October 18 until 2003 November 3 when three large active regions, consisting of spots and faculae transited the solar disk. Daily snapshots of the distributions of magnetic features on the solar surface are shown in Figure 4. On 2003 October 18 (day 1 in Figures 3 and 4) a large active region just rotated onto the western part of the solar disk. As discussed previously, the faculae of the active region are especially bright when observed close to the solar limb. Consequently, on day 1 faculae exceed the effect from spots causing shift of the solar photocenter toward the active region, i.e., to the west (negative abscissa values). As the active region rotates toward the disk center the facular brightness contrast drops and at day 3 the effect of the spots surpasses that of the faculae so that the solar photocenter starts to move away from the active region, shifting it to the eastern part of the solar disk (positive abscissa values). Similarly, the active region rotating onto the disk on day 6 first attracts and then from day 7 starts to repel the photocenter. Since the active region is located at a relatively high latitude the photocenter also experiences large displacements along the Y-axis. The trajectory of the photocenter is further affected by the sunspot group emerging at day 10. Figure 4 shows that the area of the emerged group continues growing most of the time it is on the disk (until the
effect of the foreshortening makes it less visible) amplifying the displacement of the photocenter to the west. All in all, both facular and spot features affect the position of the photocenter. Furthermore, one can see that it is important to properly account not only for the solar rotation but also for the evolution of magnetic features to properly model the trajectory of the photocenter.

Displacements in Figures 2 and 3 have been calculated as they would be seen in the Gaia G filter. To better illustrate the dependence of the displacement on the spectral passband we also calculated the displacements as they would be seen in the Blue (330–680 nm) and Red (630–1050 nm) Gaia photometers as well as in the TSI, and Small-JASMINE passband. Just like passband G, the transmission curves of the blue and red photometers have been taken from the Gaia DR2. We note that Gaia astrometric measurements are only available in the G passband so that displacements in the Red and Blue passbands (similarly to the displacements in the TSI, see Section 3) are only shown to illustrate the effect of wavelength.

Figure 5 shows that displacements in the TSI and in all Gaia filters closely correlate with each other. The displacements in the TSI are quite close to those in the G filter (being on average only 3% smaller, see right panel of Figure 5). The largest displacement is found in the blue filter and the smallest in the red filter (16% larger and 15% smaller than in the G passbands, respectively).

The behavior of the displacements in the infrared Small-JASMINE passband is quite different: they show only moderate correlation with the displacements in the Gaia G filter and also their amplitude is less than half that in the Gaia G.
filter. Interestingly, Figures 5(c), (d) indicate that the displacements in the Small-JASMINE passband appear to be significantly smaller than those in the TSI. This implies that the effect of the compensation between facular and spot components of the displacements which caused TSI and Small-JASMINE trajectories to look very similar in Figures 1(b), (c) is smaller for the real distribution of solar magnetic features than for the case of the transit of single non-evolving active region. This can be explained, e.g., by considering displacements caused by the transits of active regions consisting of only faculae (since the spot part of active regions decays much faster than facular there are many such active regions on the Sun). Such a facular active region would lead to a significant displacement of the solar photocenter in the TSI but due to a small facular infrared contrast will result in a very small displacement in the Small-JASMINE passband. One can, indeed, see that Figure 5(d) contains a lot of blue points close to the X-axis, i.e., points with noticeable displacement in the Gaia G passband but with very small displacement in the Small-JASMINE passband.

In Figures 6 and 7 we plot the X- and Y-displacements in the Gaia G passband, respectively, as a function of time. One can see that that the amplitude of the jitter in the position of the solar photocenter is clearly modulated by solar activity, i.e., it is small during the activity minimum (2008–2009) and increases toward the maxima of cycles 23 and 24. As discussed above, the conspicuous annual period in the Y-displacements is brought about by the change of the visible solar inclination caused by the Earth’s orbital movement.

Figure 5. The displacements (relative to the solar disk center) calculated in Blue (panel (a)) and Red (panel (b)) Gaia passbands, as well as in the TSI (panel (c)) and in the Small-JASMINE passband (panel (d)) as functions of displacements calculated in the Gaia G passband. Each blue asterisk points to the daily values of the corresponding displacements. Solid black lines indicate the linear regression to the plotted dependences. Dashed lines represent identity lines.

Figure 6. Displacements of the solar photocenter along the X-axis vs. time. Shown are total displacements (top panel) as well as their facular (middle panel) and spot (bottom panel) components. The displacements are calculated in the Gaia G passband. Horizontal blue lines in each of the panels indicate corresponding values of the displacement standard deviation.

Figure 7. The same as Figure 6 but for the displacement along the Y-axis.
5. Discussion and Conclusions

We have extended the SATIRE model of solar irradiance variability to calculate the displacement of the solar photocenter caused by the magnetic activity of the Sun. Such a displacement is caused by the dark spots and bright facular features on the solar surface and is often referred to as the astrometric jitter in the literature (see, e.g., Makarov et al. 2010; Morris et al. 2018). We have calculated the displacements as they would be seen in the Gaia and Small-JASMINE passbands as well as in the TSI. The displacements are mainly visible on the timescale of the solar rotation and are caused by the transits of sunspot and facular features over the visible solar disk as the Sun rotates. Our calculations indicate that facular and spot components of the displacement have comparable amplitudes and thus the effect of faculae on the position of the photocenter cannot be neglected as has been previously done in a number of studies.

The rms amplitude of the displacements from the solar disk center as they would be seen in the Gaia G passband (\(R_{G}(t)\), see Figure 5) during 2000 (a year of high solar activity) was about 0.24 mR\(_{\text{Sun}}\). For comparison, Makarov et al. (2010) found a somewhat smaller value of 0.91 \(\mu\)as \(\approx 0.19\) mR\(_{\text{Sun}}\) for the same period. One source of the difference between these estimates might be the fact that Makarov et al. (2010) used ground-based data for obtaining distribution of magnetic features on the Sun and for assessing their brightness contrasts. At the same time, our calculations for 2000 rely on a distribution of magnetic features obtained from more accurate space-born data (see detailed discussion in Yeo et al. 2014) and on calculated contrasts of magnetic features (Unruh et al. 1999). Our model shows that the amplitude dropped to about 0.04 mR\(_{\text{Sun}}\) for 2008 (a year of low solar activity). At the same time individual peaks of the displacement along the solar equator often exceed 0.5 mR\(_{\text{Sun}}\) (see Figure 6) with the most notable peak being in 2003 November, when a large sunspot group caused an excursion of almost 1.5 mR\(_{\text{Sun}}\) along the solar equator. Consequently, the amplitude of the solar astrometric jitter in the Gaia G passband is comparable to the signal caused by the Earth rotating around the Sun (about 0.6 mR\(_{\text{Sun}}\)) but it is significantly lower than the signal produced by the orbital motion of Jupiter (about 1060 mR\(_{\text{Sun}}\)). The amplitude of the jitter in the Small-JASMINE passband is expected to be more than two times smaller than that in the Gaia G passband.

The peak-to-peak amplitude of the solar jitter in the Gaia G passband reaches roughly 1 mR\(_{\text{Sun}}\) which corresponds to 0.5 \(\mu\)as for the Sun located 10 pc away from the observer (which agrees with the result of Lagrange et al. 2011, see, e.g., their Figure 1). Interestingly, this number appears to be consistent with an estimate of 0.35–0.9 \(\mu\)as given in Section 2.

This is by far smaller than the along-scan single-epoch precision of the Gaia measurements for the brightest stars (34 \(\mu\)as). At the same time the magnetic activity-induced displacements are expected to increase for more variable stars and for main-sequence stars with larger radii. In particular, a simple estimate performed in Section 2 suggests that the amplitude of the photometric jitter can reach up to 15 \(\mu\)as for the most variable G-stars.

The calculations presented in this paper have been performed for the Sun as it would be seen from its equatorial plane. Recently, Işık et al. (2018) developed a model for flux emergence and transport on stars more active than the Sun, while Nèmec et al. (2020a, 2020b) proposed a method for calculating the disk distribution of magnetic features as it would be seen out of the ecliptic. Finally, Witzke et al. (2018, 2020) showed how the contrasts of magnetic features depend on the stellar fundamental parameters. In the next papers we plan to follow up on these studies and extend calculations of stellar jitter to: (a) the Sun observed from an arbitrary inclination; (b) the stars with near-solar magnetic activities but various fundamental parameters; (c) stars more active than the Sun.

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