Long-Term Datasets for the Understanding of Solar and Stellar Magnetic Cycles
Proceedings IAU Symposium No. 340, 2018
D. Banerjee, J. Jiang, K. Kusano & S. Solanki, eds.

doi:10.1017/S1743921318001175

Four years of starspot evolution on an active F-type ultra-fast rotator KIC 6791060

Subhajeet Karmakar[1]†, Jeewan C. Pandey[1], Igor S. Savanov[2], Ashish Raj[3], E. S. Dmitrienko[4], Yurij Pakhomov[2] and D. K. Sahu[3]

[1]Aryabhatta Research Institute of observational sciencES (ARIES), Manora Peak, Nainital 263002, India

[2]Institute of Astronomy, Russian Academy of Sciences, ul. Pyatniskaya 48, Moscow 119017, Russia

[3]Indian Institute of Astrophysics, Koramangala, Bangalore 560034, India

[4]Lomonosov Moscow State University, Sternberg Astronomical Institute, Universitetskii pr. 13, Moscow 119234, Russia

Abstract. Using the data obtained from *Kepler* satellite, we have analyzed an F-type ultra-fast rotator KIC 6791060. We derive a rotational period of 0.34365±0.00004 d. Multiple periodicity with a period separation of ∼0.00016 d was detected, which appears to be a result of the relative velocity between the multiple spot-groups in different stellar latitudes due to the surface differential rotation. Modeling of the surface inhomogeneities using the light curve of 3899 epochs shows the evidence of single active longitude region. The active longitude is found to drift along the longitude at a rate similar to the detected period separation of the F-type star. The surface coverage of cool spots is found to be in the range of ∼0.07–0.44%. The low value of the spottedness can be interpreted probably due to the thinner convection zone on the F-type star.

Keywords. stars: individual (KIC 6791060) – stars: activity – stars: imaging - stars: spots – stars: rotation – stars: evolution – stars: atmospheres – stars: late-type – techniques: photometric – techniques: spectroscopic

1. Introduction

The internal structure of the F-type stars is similar to that of the Sun. In the core, the energy is transported via radiation. In the outer layer, the temperature gradient is steep enough so that convection provides the primary need of energy transport. The interface between the convection and the radiation zone is known as the tachocline. This is where the stellar magnetic field is strengthened and organized. The observational evidence of magnetic activities are the presence of starspots, short and long-term variation in spot-cycles, and flares. Observations of these activities are very essential in order to provide good constraints on present theoretical magnetic dynamo models, which are developed on the basis of the Sun.

The F-type stars with a thinner convection zone is generally expected to have a lower level of magnetic activity than that of the Sun. On the other hand, the stars in general shows very interesting behavior when the rotational velocities are very high (>40 km s^{-1}), as they are in the saturation or supersaturation ($L_X/L_{bol}=10^{-3.0}$) region of rotation activity diagram (e.g. Feigelson & Lawson 2004). Detailed analysis on ultra-fast rotators (UFRs) of solar and sub-solar massive stars are extensively done in last few decades (e.g. Speedy Mic (P=0.3804; $L_X/L_{bol}=10^{-2.27}$), AB Dor (P=0.5139; $L_X/L_{bol}=10^{-2.93}$), HK Aqr (P=0.4312; $L_X/L_{bol}=10^{-3.37}$) and LO Peg (P=0.42312;

† speaker; email: subhajeet09@gmail.com

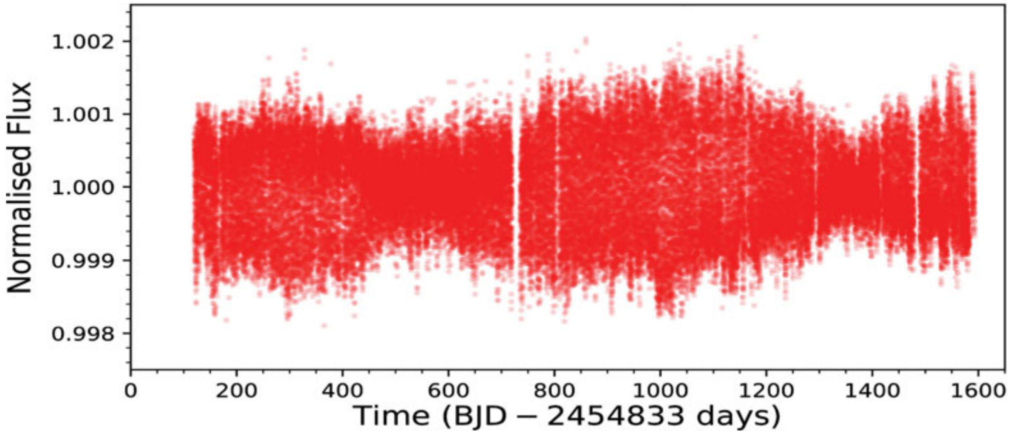

Figure 1. The four year long flare/outlier removed normalised light curve of KIC 6791060

$L_X/L_{bol}=10^{-3.0}$). However, the detailed studies of F-type UFRs are still rarely discussed in the current literature.

Here we have chosen a poorly known F-type main-sequence UFR KIC 6791060 with a period of 0.344 d (Balona 2015), V-band magnitude of 10.57 mag, and $B-V$ color of 0.44 mag (Høg *et al.* 2000) with the aims to study different magnetic activities such as the short period cycles, surface inhomogeneities, surface differential rotation (SDR) and flares. However, due to limited space in this proceeding, we only discuss our results on the evolution of surface inhomogeneities of the star. A detailed analysis of all of the magnetic activities will be discussed in Karmakar *et al.* (2018, in preparation).

The article is structured as follows: in §2 we briefly discuss the observational datasets and the data analysis techniques. In §3 we present our analysis and results on light curves and period analysis. The surface imaging is discussed in §4. Finally, a brief summary of our results is given in §5.

2. Observations and data processing

The F-type star KIC 6791060 was observed for four years from 13 December 2009 to 13 December 2013 by the *Kepler* satellite. The *Kepler* data consist of practically continuous photometry for that period. The data were taken in two different modes. In eighteen quarters, data were taken with 30-min exposures (long-cadence; LC mode) and in one quarter only it was observed with 1-min exposures (short-cadence; SC mode). For our analysis we used the *pre-search data conditioning simple aperture photometry* (PDCSAP) data in which instrumental effects are removed. The raw PDCSAP light curve obtained in LC mode. For further analysis, we have subtracted a linear fit from the light curve of each individual quarter to remove any long-term calibration errors and normalized it to its average flux.

In order to estimate the inclination angle of the star, we also obtained high-resolution spectroscopy. Six optical spectra of KIC 6791060 with a total exposure time of 3 hours were obtained between 17-th and 30-th October 2017 with optical fiber-fed Hanle echelle spectrograph (HESP) installed at 2-m telescope HCT of the Indian Astronomical Observatory (India). The resolving powers were R=30 000 & R=60 000, the signal-to-noise ratio was about 170 near λ5500 Å. Data have been reduced using standard packages available in IRAF.

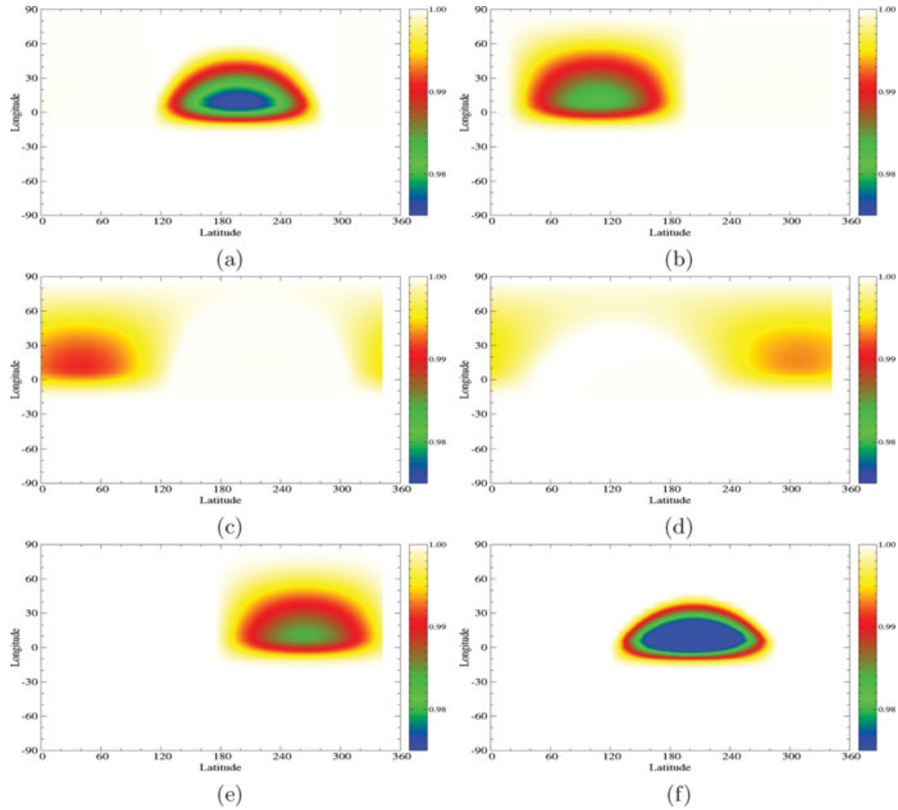

Figure 2. Few representative surface inhomogeneity maps of KIC 6791060. The colors in each plot shows the spot filling factor 'f'. The maps corresponds to the time-range in JD (2454833+) as follows: (a)120.54–120.87 day, (b) 403.03 – 403.36 day, (c) 532.58 – 532.91 day (d) 554.57 – 554.90 (e) 639.13 – 639.45 day (f) 773.84 – 774.15 day

3. Light curves and period analysis

The flare/outlier-removed, flat, normalized light curve is shown in Fig. 1. The light curve displays both short- and long-term flux variations with a high amplitude. We searched for periodicities in the data using the Scargle-Press period search method (Scargle 1982; Press & Rybicki 1989). The highest peak in the power spectrum corresponds to a period of 0.34365±0.00004 d, which could be the rotation period of the star. Another peak was also seen in the power spectrum which corresponds to a period of 0.34349±0.00004 d and is separated by 0.00016 d from the rotational period. This multiple periodicities could be a result of multiple spot groups located in different latitude while the difference in period could be due to the SDR of the star.

4. Surface imaging with light curve inversion technique

Dark spots move across the stellar disk due to the stellar rotation and thus modulate the total brightness with the rotational period of the star. In order to determine locations of spots on the stellar surface, we have performed inversion of the phased light curves into stellar images using the light curve inversion code (iPH; see Savanov & Strassmeier 2008; Karmakar *et al.* 2016; Savanov *et al.* 2016). The model assumes that, due to the low spatial resolution, the local intensity of the stellar surface always has a contribution from the photosphere (I_P) and from cool spots (I_S) weighted by the fraction of the surface covered by spots, i.e., the spot filling factor f by the following relation: $I = f \times I_P + (1 - f) \times I_S$;

with $0 < f < 1$. The inversion of a light curve results in a distribution of the spot filling factor (f) over the visible stellar surface.

We could make 3899 time-intervals as each interval corresponds to a single rotation of the star. Individual light curves were analyzed using the iPH code. In our modeling, the surface of the star was divided into a grid of $6^\circ \times 6^\circ$ pixels, and the values of f were determined for each grid pixel. We adopt the photospheric temperature of KIC 6791060 to be $\sim$6343 K (Luo *et al.* 2016) and the spot temperature to be 1000 K lower than the photospheric temperature. The stellar astrophysical input includes a set of photometric fluxes calculated from an atmospheric model by Kurucz (1992) as a function of temperature and gravity. For KIC 6791060 we precisely determined the inclination angle with the analysis of high-resolution HCT spectra, and we fixed the inclination angle at 10.6°. Various test cases were performed to recover the artificial maps and include data errors and different input parameter errors which demonstrate the robustness of our solution to various false parameters.

Fig. 2 shows six representative reconstructed surface inhomogeneity maps of KIC 6791060, corresponding to the time mentioned in the caption. The surface maps reveal that the spots have a tendency to concentrate at only one longitudes corresponding to single active regions on the stellar surface. Furthermore, the active longitude is found to be shifted along the longitude. We have also estimated the spottedness of the F-type star which varies from 0.07–0.44%. This shows a low level of magnetic activity in comparison to the Sun.

5. Summary

Using the *Kepler* long-cadence data, we derived the Scargle-Press periodogram. We found the rotational period of the F-type UFR KIC 6791060 to be 0.34365 ± 0.00004 d. The variable shape and amplitude of the light curves of KIC 6791060 at 3899 epochs indicate the temperature inhomogeneities on its surface. A modeling of these observations reveals that the stellar surface is spotted up to 0.44%, which is less than that of the Sun. A UFR with high rotational velocity, showing such low activity (in terms of spottedness) can only be interpreted as a cause of thinner convection zone on the F-type star. We have also analyzed the flares, surface differential rotations of the star. The detailed study of these analyses will be published somewhere else (Karmakar *et al.* 2018, in preparation).

This work was done under the Indo-Russian DST-RFBR project reference INT/RUS/RFBR/P-271 (for India) and Grant RFBR 17-52-45048 IND_a (for Russia). We acknowledge the NASA Science Mission directorate and the *Kepler* team for the observation, collecting the data and making it publicly available.

References

Balona L. A., 2015, MNRAS, 447, 2714
Feigelson E. D., Lawson W. A., 2004, ApJ, 614, 267
Høg E. *et al.*, 2000, A&A, 355, L27
Karmakar S. *et al.*, 2016, MNRAS, 459, 3112
Kurucz R. L., 1992, in IAU Symposium, Vol. 149, The Stellar Populations of Galaxies, Barbuy B., Renzini A., eds., p. 225
Luo A.-L. *et al.*, 2016, VizieR Online Data Catalog, 5149
Press W. H., Rybicki G. B., 1989, ApJ, 338, 277
Savanov I. S. *et al.*, 2016, Acta Astron., 66, 381
Savanov I. S. & Strassmeier K. G., 2008, Astronomische Nachrichten, 329, 364
Scargle J. D., 1982, ApJ, 263, 835