Multi-wavelength Spectral Analysis of Ellerman Bombs Observed by FISS and IRIS

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Received 2016 November 9; revised 2017 February 21; accepted 2017 March 9; published 2017 March 31

Abstract

Ellerman bombs (EBs) are a kind of solar activity that is suggested to occur in the lower solar atmosphere. Recent observations using the Interface Region Imaging Spectrograph (IRIS) show connections between EBs and IRIS bombs (IBs), which imply that EBs might be heated to a much higher temperature ($8 \times 10^7$ K) than previous results. Here we perform a spectral analysis of EBs simultaneously observed by the Fast Imaging Solar Spectrograph and IRIS. The observational results show clear evidence of heating in the lower atmosphere, indicated by the wing enhancement in H$\alpha$, Ca II 8542 Å, and Mg II triplet lines and also by brightenings in images of the 1700 Å and 2832 Å ultraviolet continuum channels. Additionally, the intensity of the Mg II triplet line is correlated with that of H$\alpha$ when an EB occurs, suggesting the possibility of using the triplet as an alternative way to identify EBs. However, we do not find any signal in IRIS hotter lines (C II and Si IV). For further analysis, we employ a two-cloud model to fit the two chromospheric lines (H$\alpha$ and Ca II 8542 Å) simultaneously, and obtain a temperature enhancement of 2300 K for a strong EB. This temperature is among the highest of previous modeling results, albeit still insufficient to produce IB signatures at ultraviolet wavelengths.

Key words: line: profiles – radiative transfer – Sun: activity – Sun: atmosphere

1. Introduction

Ellerman bombs (EBs) are a kind of short-lived, small-scale solar activity that shows intense brightenings in the H$\alpha$ wings (Ellerman 1917). Recent observations revealed that EBs are also visible in the wings of Ca II H/K (Matsumoto et al. 2008; Rezaei & Beck 2015), Ca II 8542 Å (Yang et al. 2013; Kim et al. 2015; Rezaei & Beck 2015), He I D$_3$, and He I 10830 Å (Libbrecht et al. 2017) and in the ultraviolet (UV) continuum of 1600 and 1700 Å (Vissers et al. 2013; Rezaei & Beck 2015; Tian et al. 2016) and are almost transparent in the optical continuum, in neutral metal lines (Na I D and Mg I b; Rutten et al. 2015), and in hotter coronal lines (171 and 193 Å channels; Vissers et al. 2013; Tian et al. 2016). The variety of visibility in different spectral lines suggests that EBs occur in the lower atmosphere, usually in the upper photosphere to the lower chromosphere. A review of studies on EBs can be found in Georgoulis et al. (2002) and Rutten et al. (2013).

Most EBs appear near the polarity inversion line and are associated with flux emergence (Pariset et al. 2007; Watanabe et al. 2008; Yang et al. 2013, 2016; Danilovic et al. 2016; Reid et al. 2016) or moat flows (Watanabe et al. 2011; Vissers et al. 2013). Numerical simulations have shown that newly emerged magnetic fluxes can interact with one another or with pre-existing magnetic fields and cause magnetic reconnections (Isobe et al. 2007; Archontis & Hood 2009; Nelson et al. 2013). Line-of-sight mass flows as outflows from magnetic reconnections can be derived from spectral line profiles using the bisector method, which shows upflows in the lower chromosphere and downflows in the photosphere (Matsumoto et al. 2008; Yang et al. 2013). EBs can also be associated with a small-scale loop (Nelson et al. 2015), a surge (Matsumoto et al. 2008; Yang et al. 2013; Pasechnik 2016), or jets (Watanabe et al. 2011; Reid et al. 2015).

There are two approaches to estimate temperature increase in EBs based on observed spectral lines. One is to calculate non-LTE semi-empirical models that satisfactorily reproduce the observed line profiles. Available calculations have indicated that the temperature increase is in the range of a few hundreds of kelvins to 3000 K (Fang et al. 2006; Sucas-Navarro et al. 2006; Bello González et al. 2013; Berlicki & Heinzel 2014; Li et al. 2015; Kondrashova 2016). The second approach is to fit the spectral lines using some simplified models. In this regard, Hong et al. (2014) proposed the two-cloud model, which assumes that the EB atmosphere is comprised of two characteristic layers, a lower (relatively hot) layer responsible for the line wing emission and an upper (relatively cool) layer for the line center absorption. By fitting the observed H$\alpha$ line profiles, they derived a temperature increase in EBs (the lower layer) of around 1000 K, consistent with previous results.

Recently, the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014) discovered some “hot explosions” that are thought to occur in the lower atmosphere (Peter et al. 2014). They are also referred to as IRIS bombs (IBs), which have many similarities to EBs, except that the former exhibit enhanced UV line emissions. However, Judge (2015) suggested that IBs occur in the lower/mid chromosphere or above, as a result of Alfvénic turbulence. Kim et al. (2015) studied an IB that appeared to be a very weak EB in the line wings of H$\alpha$. Vissers et al. (2015) studied five EBs, all of which have corresponding IBs. They suggested that the top of the flare-like EBs can be heated to a high temperature, so that the EBs are also visible in IRIS Si IV lines. Tian et al. (2016) studied 10 IBs and found that 6 of them are associated with EBs. Libbrecht et al. (2017) studied three EBs with IB signatures and estimated the upper limit of the temperature to be $2 \times 10^5 - 10^5$ K by assuming that the line broadenings are caused by thermal Doppler motions. These observations suggest a possible link between EBs and IBs—that is, EBs might be hotter than predicted by previous models.

Therefore, two key questions regarding EBs are the forming height and the temperature enhancement, which are associated

https://doi.org/10.3847/1538-4357/aa671e
with the mechanism of EBs as well as with their relationship to IBs. We have investigated the temperature enhancement by fitting the Hα profiles of EBs in our previous work (Hong et al. 2014). However, there remains some uncertainty when only one spectral line is used. In order to improve the reliability of results, one needs to use more spectral lines with different formation heights. In this work, we fit the profiles of Hα and Ca II 8542 Å lines simultaneously. We also choose a very strong EB and a relatively weak one to see the difference in their spectral lines. More importantly, we need to check how much temperature enhancement the strong EB can generate.

For the above purpose, we investigate EBs based on multi-lines observed simultaneously with the Fast Imaging Solar Spectrograph (FISS; Chae et al. 2013) and IRIS. We present the imaging and spectral features of the EBs in Section 2. In Section 3, we apply the two-cloud model to fit the Hα and Ca II 8542 Å lines simultaneously, and present the results. A discussion of the implications of the results and a summary are given in Section 4.

2. Observations

Observations were performed simultaneously by FISS and IRIS of a target active region, NOAA 12401 (241E, 317S), on 2015 August 16. FISS is attached to the 1.6 m New Solar Telescope (NST; Cao et al. 2010; Goode & Cao 2012) at Big Bear Solar Observatory, which can obtain two-dimensional spectral data from dual bands simultaneously using a scanning mode, producing high-resolution and high-cadence spectra of Hα and Ca II 8542 Å. The scanning has a cadence of 40 s, covering a field of view (FOV) of 40″ × 40″, with a pixel size of 0″16. The spectral resolution is 19 mÅ for Hα and 26 mÅ for Ca II 8542 Å.

IRIS observed the same region at the same time and scanned over a small pore for 1 hr from 19:00 UT. IRIS can provide spectral scan data and slit-jaw images (SJIs) at near-UV (NUV) and far-UV (FUV) lines simultaneously. These lines have formation temperatures of tens of thousands of kelvins and are thus good diagnostics of the upper chromosphere and transition region. In the observation, IRIS targeted a small sunspot using a 40 s cadence raster scan. The cadence of each scanning step is 1.2 s, which seems too short to ensure a sufficient signal-to-noise ratio for lines in the FUV bands. Thus, we performed a 3 × 3 spatial bin for the FUV spectra, which resulted in an actual spatial sampling of 1″05 × 1″05. The NUV spectra and SJIs were not modified. The spectral scanning covers an FOV of 11″ × 119″. All SJIs have a cadence of 10 s.

The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) can provide extreme UV continuum images at 1700 Å, with a time cadence of 24 s and a pixel size of 0″6. Such an extreme UV continuum is believed to originate from the temperature minimum region and upper photosphere (Lemen et al. 2012). The Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) provides the line-of-sight magnetic field with the same pixel size, but with a cadence of 45 s.

Before further analysis, we need to co-align the images from the different instruments using the same method mentioned in Hong et al. (2016). In this case, IRIS SJI 2832 Å is used as the reference image. The accuracy of co-alignment between the NST and IRIS images is within 0″7.

2.1. Imaging Observations

The active region we observed was quite productive and had produced several small flares during the 3 days before the observation time. Thus, it is a promising region for detecting EBs. We identified one strong and one weak EB during the 1 hr observation, both with a heliocentric angle of about 30°. Figure 1 shows the time evolution of reconstructed images of the strong EB at different parts of the Hα line, which reveal obvious brightenings at the line wings but no clear response at the line center, as well as the line-of-sight magnetic field. The lifetime of this EB is approximately 6 minutes, which is within the typical range. From the magnetic structure, we can find a small negative polarity near the pore, as delineated by the green contours. Compared to the strong magnetic field in the pore, the negative polarity is quite weak, though still visible. Thus, the strong EB lies between two opposite polarities, where magnetic reconnection could take place. The weak EB also lies near the rim of the negative polarity, but to the south of it (Figure 1).

The evolution of the line-of-sight magnetic flux of the negative and positive polarities is shown in Figure 2. The negative polarity newly emerges about 15 minutes before magnetic cancellation takes place and the strong EB occurs. The weak EB occurs later. The evolution of the positive polarity is not exactly the same as that of the negative polarity, because the positive flux mainly comes from the pore, which is relatively large and is less influenced by the newly emerged negative polarity. However, the magnetic fluxes of both polarities decrease during the two EBs. One can also see from the contours in Figure 1 that the area of the negative polarity is gradually decreasing. The magnetic flux cancelation rate can be estimated to be about 2.2 × 10¹⁴ Mx s⁻¹, within the typical range for EBs (Reid et al. 2016).

Figure 3 shows multi-wavelength images and the magnetic structure of the EB at the peak time of Hα intensity. We also detect brightenings of the EB in the AIA 1700 Å and IRIS SJI 2832 Å images (Figures 3(d) and (f)). As the formation layer of the UV continuum is roughly at the temperature minimum region, brightenings in these wavebands provide evidence of heating in the lower atmosphere. However, for the remaining three IRIS SJIs (Figures 3(g)–(i)), there appears almost no response in the EB region. This implies that the heating of this EB is not strong enough for the local temperature to reach the formation temperature of the Mg II line, which is approximately 10,000 K.

2.2. Spectral Observations

2.2.1. Hα and Ca II 8542 Å Lines

We show the FISS and IRIS line spectra for the strong EB in Figure 4 and those for the weak EB in Figure 5. The dashed lines in these two figures denote the pre-EB line profiles, which are the profiles at the same position but before the occurrence of EBs. It can be seen that for both EBs, the Hα line wings are significantly enhanced at the peak time as compared to the pre-EB profiles, while the line center remains almost unchanged. Similar features appear in the Ca II 8542 Å line, although the line wing enhancement is less significant than that in the Hα line. In both lines, the intensity enhancement extends over broad wings with the magnitude gradually decreasing toward the far wings, indicating that heating occurs within a restricted layer in the lower atmosphere.
Figure 1. Time series of reconstructed images from FISS and HMI observations showing the evolution of the strong EB. From left to right, the four columns show the Hα images at the blue wing (−1 Å), the line center, and the red wing (+1 Å) and the line-of-sight magnetic field (red for negative polarity and blue for positive), respectively. The green lines are the contours of magnetic field strengths of −10 and −30 G. The red arrow points to the weak EB, which is marginally visible at ±1 Å.
in the EB region. The integration ranges for Mg II lines are carefully selected so that the influence of the continuum is reduced to the least. In our case, we set the integration range to ±0.25 Å for the Mg II triplet lines and to ±0.5 Å for the Mg II k/h lines. The intensities have been normalized to the corresponding pre-EB values. All the data points in Figure 6 come from the 16 pixels that cover the region of the strong EB over the whole lifetime. Clearly, there is a strong correlation between the Mg II triplet lines and the Hα line. The few points with relative intensities less than 1.0 in the two upper panels come mainly from the pixels that are located at the edge of the EB. In addition, there seems to be no correlation between the Mg II k/h lines and the Hα line for the strong EB studied here.

2.2.2. Mg II Lines

For the strong EB, spectra at the Mg II 2796 window (Figure 4(c)) show an enhancement of approximately 20% in the UV continuum, corresponding to the brightening in SJI 2832 Å. However, the most striking feature in this wavelength window is the enhancement of the Mg II triplet lines. These lines are optically thick and form just above the temperature minimum region (Pereira et al. 2015). Pereira et al. (2015) found that for these lines, if there is heating in the lower atmosphere, there appears emission in the line wings while the line center remains in absorption, which is just what we observed. We further find that the triplet lines have a profile shape that resembles that of Hα, which has an obvious enhancement in the line wings but is less influenced in the line center (denoted by blue arrows in Figure 4(c)). By contrast, for the Mg II k/h lines, we can hardly see any obvious change in line intensity when the strong EB occurs. The width of the Mg II k/h lines does not change either during the strong EB. For the weak EB, besides the enhancement in the Mg II triplet line wings, there is an enhancement in the Mg II k/h line wings (Figure 5(c)).

Figure 6 shows a scatter plot of the wavelength-integrated intensities of the Mg II triplet lines versus that of the Hα line in the EB region. The integration ranges for Mg II lines are carefully selected so that the influence of the continuum is reduced to the least. In our case, we set the integration range to ±0.25 Å for the Mg II triplet lines and to ±0.5 Å for the Mg II k/h lines. The intensities have been normalized to the corresponding pre-EB values. All the data points in Figure 6 come from the 16 pixels that cover the region of the strong EB over the whole lifetime. Clearly, there is a strong correlation between the Mg II triplet lines and the Hα line. The few points with relative intensities less than 1.0 in the two upper panels come mainly from the pixels that are

2.2.3. C II and Si IV Lines

As already reflected by the SJI 1330 and 1400 Å images, the profiles of the C II and Si IV lines show no change in the strong EB. Despite the large amount of noise, these lines show no Doppler shift and no increase in line width or intensity (Figures 4(d)–(f)). This implies that the strong EB under study is not an IB that is heated to the transition region temperatures. The weak EB here is not an IB either (Figures 5(d)–(f)).

3. Data Analysis

3.1. Two-cloud Model

We use the two-cloud model proposed by Hong et al. (2014) to investigate the temperature enhancement caused by the EB in the lower atmosphere. The lower cloud represents the energy release region, while the upper cloud represents some overlying chromospheric fibrils. The temperature enhancement of the lower cloud can thus be deduced from the increase of the source function there, after the observed EB profiles are fitted with synthetic profiles from the two-cloud model. The line profiles used in this model are contrast profiles, defined as

\[ C(\lambda) = \frac{I_{\text{EB}} - I_q}{I_q}, \]

where \(I_{\text{EB}}\) is the original profile at the brightest point in the EB region and \(I_q\) is the profile at the same location before the EB. As described in Hong et al. (2014), the physical parameters within each cloud are assumed to be constant. Note that Hong et al. (2014) fit only the Hα line. In this work, we make a significant improvement by fitting the Hα and Ca II 8542 Å lines simultaneously. Doing so can reduce uncertainties in the fitting parameters, particularly in the temperature. Since the lower cloud is the origin of line wing emissions for both lines, the temperature increase there can be more constrained by observations considering that the two lines have different sensitivities to the local temperature.

As was done in Hong et al. (2014), we need to reduce the number of free parameters in the model for the fitting to be practical. The departure coefficients of the lower and upper levels of the hydrogen atom responsible for Hα are obtained from the VAL-C model (Vernazza et al. 1981). Rutten (2016) calculated the departure coefficients of the lower and upper levels of Ca II associated with the 8542 Å line and showed that the coefficients approach unity near the temperature minimum region where EBS are thought to occur (see the second row of their Figure 1). For simplicity, we assume that the departure coefficients of Ca II are unity in the lower cloud.

As is well known, the emergent intensity relies on two key parameters, the line source function and the optical depth of the cloud. Sometimes, it is difficult to distinguish which one plays a major role in producing the intensity increase. This makes the fitting results not unique if the two parameters are both free. In fact, the line source function and the absorption coefficient depend on the local temperature in different ways. Here, we first check how the optical depth of the cloud may vary with the local temperature. Under the condition of local thermodynamic equilibrium (LTE), the line absorption coefficient (or optical
depth if given a fixed geometric depth) should vary sensitively with the local temperature, which is the sole factor determining the excitation and ionization of an atom, as clearly revealed in calculations by Rutten (2016). However, in non-LTE cases, radiative excitation and ionization may be important, which depend on the radiation field from beyond the local region. This makes the problem more complex.

Here, we perform a test to show how the line absorption coefficient (optical depth) could vary under non-LTE circumstances. We solve the statistical equilibrium and charge conservation equations for the lower cloud simultaneously. We consider two atoms, hydrogen and singly ionized calcium.

The number density of hydrogen is set to $10^{15}$ cm$^{-3}$, which is a typical value in the temperature minimum region (Vernazza et al. 1981). A model atom of three levels plus a continuum for hydrogen and a model atom of five levels plus a continuum for Ca II are adopted. Because of a quite low temperature in this region, metals have a larger contribution to electron density than hydrogen. Here, we assume an extra contribution of $-N_{H}$ to the electron density from metals in the charge conservation equation. The photoionization cross sections are taken from Shine & Linsky (1974). All other atomic data are adopted from Cox (2000). At the region near the temperature minimum, the background radiation field is mostly from the photosphere and...
has little dependence on the local temperature. Here, we assume a constant radiation temperature of 5700 K.

Figure 7 shows the dependence of the number densities of the lower levels associated with the spectral lines of interest on the local temperature. It is seen that under LTE, the curves (dashed) are similar to previous results (also see Figure 5 of Rutten 2016), while in non-LTE cases, the curves (solid) are quite different. Qualitatively, in the lower-temperature domain \( T < 10,000 \) K, the number density at the lower level varies insensitively to the local temperature under non-LTE, in sharp contrast to the LTE case. That is to say, even though there occurs a temperature increase of several thousand kelvins in the EB, there seems very little increase in the number density of the lower level. We then calculate the value of the optical depth at the line center for the lower cloud, assuming the geometric thickness of the EB region to be 100 km near the temperature minimum region (Rutten 2016). The result is 0.5 for H\( \alpha \) and 2.2 for Ca\( \text{II} \) 8542 Å, which are then adopted as the optical depth of the lower cloud for the pre-EB atmosphere. The optical depth of the lower cloud for the EB atmosphere is a varying parameter that can be fitted reasonably as long as it does not vary considerably as shown above.

3.2. Fitting Results

The two chromospheric lines and their fitting results for the strong EB at its peak time are shown in Figure 8. As was done in Hong et al. (2014), we introduce random noises to the profiles and repeat the fitting 10,000 times. This is used to derive the standard deviation of the fitting results. Based on the parameters for the best fitting, we deduce a temperature enhancement of 2300 ± 20 K in the lower cloud where the EB occurs. Such a temperature increase over the quiescent status is quite large but still within the typical range. We also find that the optical depths of the two chromospheric lines vary. For H\( \alpha \), the optical depth at the line center rises from 0.5 to 0.7 ± 0.05,
while for Ca II 8542 Å, it decreases from 2.2 to 0.4 ± 0.07. This can be explained by the change in the lower-level populations. When there is a temperature increase, more hydrogen atoms are excited to the lower level of H α from the ground level, while ionization is dominant for Ca II, resulting in a relatively smaller population at the lower level of Ca II 8542 Å.

We should mention that the fitting results are more or less influenced by the hydrogen number density and the radiation temperature, because these two parameters are essential to the optical depth. We have also tested different values of these parameters. Generally speaking, a larger temperature increase is expected when the initial optical depth is smaller. Quantitatively, the deduced temperature increase can change by about 500 K when the hydrogen number density is changed by three times or the radiation temperature is changed by 5%. We think that near the temperature minimum region of the EB, it is unlikely that these two parameters undergo more changes.

4. Summary and Discussion

We analyzed the spectral data of EBs observed by NST and IRIS and fit the two chromospheric lines simultaneously using the two-cloud model. Brightenings in the AIA 1700 Å and IRIS SJI 2832 Å images and an enhancement in the wings of Mg II triplet lines confirm that there is heating in the lower atmosphere. For the strong EB studied, the relative enhancement at the near wing (∼±0.8 Å) of H α can reach as much as 0.8, one of the largest values among reported observations. However, we do not find a clear response of IRIS Mg II k/h and hotter lines in our case, except for some enhancement in the wings of Mg II triplet lines. Spectral fitting with the two-cloud model yields a temperature enhancement of 2300 K in the temperature minimum region, still far below the formation temperature of the Mg II k/h and Si IV lines.

The enhancement of Mg II triplet lines in the EB region is consistent with previous observation and simulation results (Pereira et al. 2015; Vissers et al. 2015). The formation height
of these triplet lines lies in the lower atmosphere (Pereira et al. 2015), similar to the formation height of \( \text{H} \alpha \) line wings. In fact, we find that in the EB region, the intensity of \( \text{Mg} \ II \) triplet lines correlates well with that of \( \text{H} \alpha \). This suggests an alternative way to identify EBs using the \( \text{Mg} \ II \) triplet that can be routinely observed by IRIS. A statistical study based on more events is required to validate this proposition.

Recently, there has been heated discussion on the relationship between EBs and IBs. In some events, EBs and IBs are indeed closely related or refer to the same phenomenon. Some of the EBs studied by Vissers et al. (2015) showed typical IB features, with a large width of Si \text{IV} \) profiles and an enhancement in \( \text{Mg} \ II \) k/h wings. However, although the strong EB studied here seems to have a large temperature enhancement, there appear almost no IB features. In fact, Tian et al. (2016) found that only a small fraction of EBs are heated to IB temperatures, while most EBs do not have any IB signature. The strong EB studied here just belongs to the latter category, although a fairly large temperature increase is derived by spectral fitting.

However, it is interesting that for the weak EB, we do see some weak enhancement in the \( \text{Mg} \ II \) k/h line wings. Considering that the \( \text{H} \alpha \) and \( \text{Ca} \ II 8542 \) Å lines are weaker in this EB, the derived temperature increase should be smaller than that in the strong EB. Therefore, our model, simplified by a composition of two clouds but essentially one-dimensional, cannot explain the observed broader \( \text{Mg} \ II \) k/h line profiles without worsening the fitting to the \( \text{H} \alpha \) and \( \text{Ca} \ II 8542 \) Å lines.

In the future, it should be an interesting topic to further clarify the relationship between EBs and IBs. In this regard, more coordinated observations by ground-based telescopes and IRIS are needed. In particular, for IBs, a synthetic model is

Figure 6. Scatter plot of the line intensities of \( \text{Mg} \ II \) triplet and k/h lines vs. the \( \text{H} \alpha \) line intensities in the EB region. All the intensities are integrated with the wavelength and normalized to the pre-EB values. The Pearson correlation coefficient is also shown in each panel.

Figure 7. Number densities of hydrogen and singly ionized calcium at the lower levels for the \( \text{H} \alpha \) and \( \text{Ca} \ II 8542 \) Å lines, respectively, as a function of the local electron temperature. Dashed lines refer to the results under LTE, while solid lines refer to the non-LTE results. In non-LTE cases, a constant radiation temperature (5700 K) is adopted. See the text for details.
expected to combine both heating in the chromospheric lines and possible heating that produces IRIS line emissions. Radiative hydrodynamic simulations are also required to show how the two different temperature structures are physically coupled. In particular, in order to simultaneously explain all the observed lines, one probably needs to take into account the inhomogeneity and multidimensionality of the atmosphere related to EBs.

We are very grateful to the referee for their valuable comments. The authors thank the BBSO staff for their help during the observations. The BBSO operation is supported by NJIT and US NSF AGS-1250818 grants, and the NST operation is partly supported by the Korea Astronomy and Space Science Institute and Seoul National University and by the Strategic Priority Research Program of CAS (grant no. XDB09000000). IRIS is a NASA small-explorer mission developed and operated by LMSAL with mission operations conducted at NASA’s Ames Research Center and major contributions to downlink communications funded by ESA and the Norwegian Space Centre. SDO is a mission of NASA’s Living with a Star program. This work was also supported by NSFC under grants 11373023, 11403011, and 11533005 and by NKBRSF under grant 2014CB744203.

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