Firefly: the science case for a full view of the solar sphere

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Synopsis: For many years it has been an ambition of the solar and heliophysics communities to obtain a 3-D view of the entire Sun as this is critical for understanding many fundamental processes acting within and around our star; these are key questions to address for all stars, but particularly our own. To understand solar activity, we must study the structure and evolution of the seats of such activity, the so-called active regions that are regions defined by complex and highly dynamic magnetic structure. Currently we do that from a limited set of measurement and view- points constraining the science we can do. The majority of our solar observations are made near or from the Earth, but there have been notable exceptions. Steps towards measuring different views of the Sun were carried out by the Ulysses mission. Despite plans to carry remote sensing instrumentation, the spacecraft only carried in-situ instruments, but flew an extremely successful mission providing the first measurements over the Sun's poles. The NASA STEREO mission provided 2 views of the Sun in the equatorial region, from widely separated platforms but was limited due to the lack of magnetic field data and visibility of the poles. The recent ESA/NASA Solar Orbiter mission will gradually reach out of the equatorial plane and observe from 33 degrees with both remote sensing and in situ instruments providing a major step forward in studies of our star's polar regions. In recent reviews such as the JAXA/NASA/ESA next generation solar physics mission report in 2017, 5 multi spacecraft mission to provide an extended view of the Sun were proposed. In the ESA Voyage 2050 call, polar solar mission concepts were proposed to provide extensive measurements of the mysterious polar regions that have not yet been observed with imaging instruments [1] – this paper describes different technologies that allow an extended view of the poles. ESA's Vigil mission will be stationed at the Lagrange L5 point and will carry both remote sensing and in situ instruments.

This white paper indicates the support of the European and Japanese communities for the Firefly mission concept (see white paper led by Nour Raouafi). These communities have expertise from probing the interior of the Sun using helioseismology methods to solar activity and how it feeds the heliosphere. An ambitious mission such as Firefly provides extensive opportunities to answer scientific questions that remain unanswered due to our restricted views of the Sun. There are 4 science questions probing the fundamental processes of what drives the Sun's magnetic activity from the inside of the star to activity in the heliosphere. These topics are of significant consequence to the impact our understanding of every star and hence the understanding of habitability and impacts of space weather on planets.

Introduction:

The uniqueness of Firefly (see white paper entitled: FIREFLY: The Case for a Holistic Understanding of the *Global Structure and Dynamics of the Sun and the Heliosphere*' led by Nour Raouafi) is its continuous view of the entire solar globe and 3D inner heliosphere, afforded by the strategic positioning of four spacecraft. This first dedicated mission to study a complete star enables a wide range of scientific advances. This white paper describes the international interest for this mission from Europe and Japan. In the following we provide the European and Japanese perspectives and inputs to the four major science goals that Firefly is aiming to achieve.

(**1**) *Understand how surface and internal flows produce the cyclic solar dynamo, the root cause of solar activity*;

The solar cycle is one of the biggest mysteries in solar physics. The turbulence and large-scale flow are thought to maintain the solar magnetic field and its cyclic activity. However, there are serious limitations regarding both our observational and theoretical insights into the physics of the solar cycle. From a theoretical viewpoint, there are two main approaches to addressing the solar dynamo. One is the mean-field model, and the other is the 3D magnetohydrodynamic simulation. Determining the large-scale flow structure is crucial in both cases. Once internal flows and the turbulence model are prescribed, the mean-field model can reproduce important aspects of the solar cycle, including the butterfly diagram and the polarity reversals (e.g. [2]). Unfortunately, helioseismic measurements of the meridional flow remain controversial (e.g. [3], [4]). Furthermore, turbulent diffusion is essentially a free parameter in mean-field models. In 3D MHD simulations of the solar dynamo, turbulence in the convection zone is explicitly resolved (e.g. [5]). This approach does not need many assumptions, but due to insufficient resolution, several key parameters related to diffusivities, e.g. the Reynolds number, are far from their solar values. This highlights the need for detailed observations of the solar interior.

The Firefly mission would be ideal for helioseismology. Projecting the acoustic wavefield onto spherical harmonics (using all solid angles) would strongly reduce the leaks between the different p and f modes. This would in turn lead to reliable mode frequencies and inferences of the flows and wave-speed perturbations in the solar interior. A full view of the Sun will also help us to disentangle the effects on the modes due to surface magnetic fields from the solar-cycle perturbations in wave speed deep in the convection zone. Furthermore, complete spatial coverage will lead to major advances in the observation and characterization of the solar inertial modes ([6],[7]), which are quasi-toroidal modes of oscillation of the rotating convection zone. These modes have the potential to provide entirely new information about the convection zone dynamics, such as the superadiabatic temperature gradient and the turbulent viscosity deep in the convection zone. Only the Firefly mission can give access to the high-latitude modes with the lowest azimuthal orders (Figure 1).

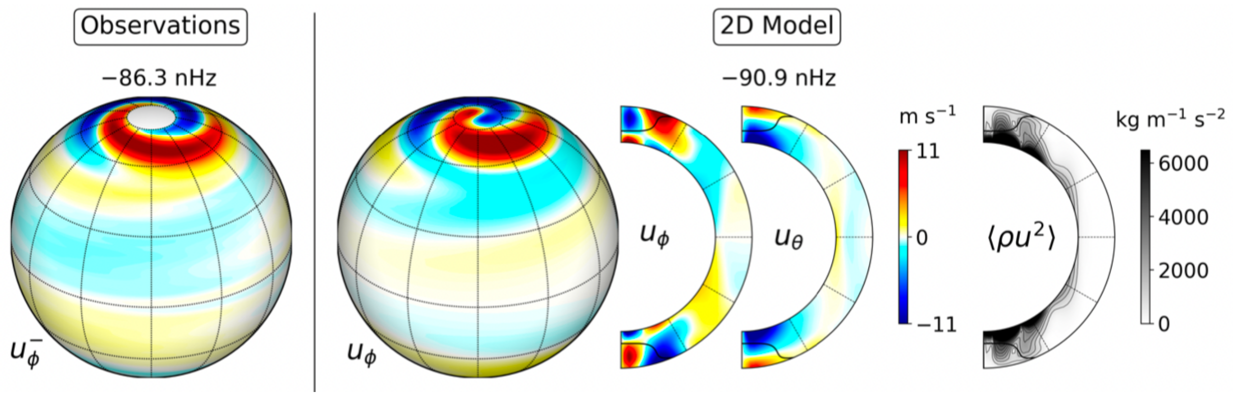

Figure 1: Observed and model eigenfunctions for the m=1 high-latitude inertial mode of oscillation. The model assumes a turbulent viscosity of 100 km^2 s^{-1} and a marginally stable convection zone. The plot on the right (gray shades) shows the kinetic energy density. The thick black curves show the critical latitudes. The gap in the observations at the critical polar regions is clear in the left plot. Figure courtesy of Yuto Bekki

The polar magnetic field at the Sun's surface is thought to seed the next solar cycle and plays an important role in the solar dynamo. Thus, the strength of the polar field provides the most successful prediction of the strength of the following solar cycle (e.g. [8]). The magnetic fields in the polar areas cannot be properly observed from the ecliptic plane due to foreshortening. Thanks to their high resolution, Hinode Solar Optical Telescope observations of the polar areas revealed the existence of strong concentrations of over 1 kG field [9]. Observations with Hinode for more than 10 years have followed a polarity reversal in the polar areas [10]. However, we still have poor knowledge of how this polarity reversal takes place and the roles of these strong concentrations, the meridional flow and differential rotation. These flows cannot be well measured at latitudes higher than 75 deg from the earth's orbit (e.g. [11], [12]). The Polarimetric and Helioseismic Imager on Solar Orbiter will improve the measurements from a 30 deg out-of-ecliptic orbit, but does not provide the temporal coverage required to fully trace the evolution of the magnetic concentrations through the cycle. Firefly will overcome these limitations and achieve detailed and continuous measurements of the flows in the high latitude areas and their interaction with the polar magnetic field.

(**2**) *Understand the conditions leading to solar explosive activity and the role of the large-scale magnetic fields*;

The development of active regions is not just important for an understanding of the evolution of the Sun's magnetic field, it also drives the processes leading to flares and coronal mass ejections (CMEs). Firefly will for the first time map the entire magnetic structure of the global photosphere from four directions and will follow *all* active regions from birth to death, providing observations of their full lifecycle, even including their pre-emerging phase. This is crucial for understanding the formation mechanism of flare-productive active regions, e.g., it is important to understand what sub-surface dynamics might relate to the formation of flare-productive regions. The comparison between local helioseismic analysis and high-resolution vector magnetic field observation for the full lifetime of active regions would enable us to discriminate between key models of active region formation, development, and solar cycle behaviour e.g. [13].

A global solar view offers a unique perspective of the generation and impact of solar explosive and eruptive events, e.g., geometrical considerations dictate that the study and development of CME source regions, the propagation of CMEs and their impacts, are best made from multiple platforms viewing from widely spaced vantage points. This has been well demonstrated by combinations of missions such as SOHO, SDO and STEREO e.g. [14] (see Figure 2). With Firefly, the capabilities take a major step forward, enabling simultaneous observations of the source active region and orthogonal observations of the associated CME that would enable a true 3D understanding of the source region, and of CME structure, development and propagation direction.

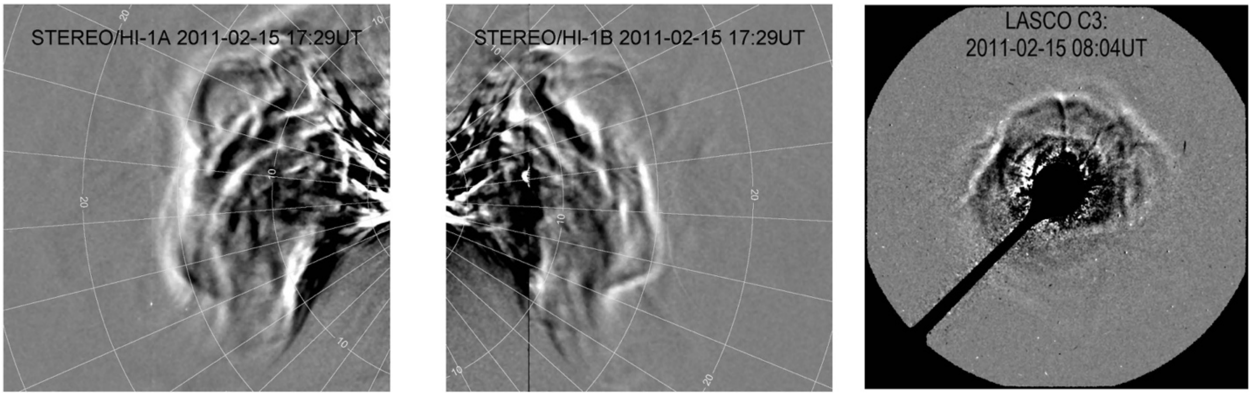

Figure 2: Images of the same CME taken from the STEREO-A and STEREO-B Heliospheric Imagers, located some 90 degrees ahead and behind the Earth (respectively), in near 1 AU orbits, along with a SOHO LASCO coronagraph image of the same CME as a head-on halo event. Such multi-platform observations are needed to reconstruct CME structure, evolution and propagation. [Credit: RAL Space, NRL, NASA]

Accurate and reliable 3D coronal magnetic field models are needed to understand solar magnetic eruptions and their triggering mechanisms. Multiple viewpoint observation would significantly improve the 3D modelling of the corona because it can solve the 180-degree uncertainty in vector magnetic field measurement. Also, comparing the model with the multiple viewpoint images of coronal loops in EUV observations provides valuable verification of the 3D modelled magnetic corona. In addition, highly reliable 3D magnetic field modelling will help identify the instabilities responsible for solar flares and solar eruptions. Magnetic instabilities driven by differing topologies will be more readily identified through 3D interpretations from multiple spacecraft e.g. kink instability [15], torus instability [16], and double-arc instability [17]. The identification of the importance of such phenomena could significantly advance our flare predictive capability [18]. Similarly, resolving the 180-degree uncertainty mentioned above is important for revealing flare triggering mechanisms because the orientation of the small-scale magnetic field on the polarity inversion line can play a crucial role in triggering flares [19].

It is important to understand the mechanism of deflection and rotation of CMEs, as well as CME-CME interaction, for improving the predictive capability of the CME geo-effectiveness and, whilst there are many interpretations from the STEREO mission that identify such phenomena e.g. [20],[21],[14], Firefly's unprecedented coverage would provide a major advance in our ability to witness CME deflection, rotation and interaction, and our ability to explore the physics of such phenomena. As part of this, with wide-angle heliospheric imaging, extending the capabilities demonstrated by STEREO [22],[23], Firefly would enable the 3D reconstruction of the underlying inner heliospheric magnetic and flow structure by mapping the so-called co-rotating interaction regions. This is critical for understanding the underlying structure of the solar wind outflow environment, including near Earth, and for reconstructing the environment into which CMEs are propagating, to better model and understand their propagation and development as CMEs interact with the large-scale magnetic field e.g. [24],[25]. All these elements will provide powerful insight to improving the predictive capabilities of CME propagation. With the polar and ecliptic views afforded by Firefly, we will observe ALL CMEs enabling a truly novel study of the mass loss of a star.

Underlying it all is the fundamental need to understand the structure and evolution of the magnetic fields of our complete star, to understand the physics relating to its activity, and to its impacts on human activities and assets. Firefly will provide this.

(**3**) *Determine how conditions in the solar wind vary with latitude and longitude in response to changing global solar conditions and throughout the solar cycle*;

The solar wind varies with latitude and longitude in response to changing global solar conditions, but the link to the global magnetic field is not fully understood. The role of the polar fields in structuring the large-scale dipolar magnetic field of the Sun is critical to understanding how the global solar wind structures fill the heliosphere, and how they vary with the solar cycle.

So far, only one mission has explored the solar wind out of the ecliptic plane. The Ulysses (1990 – 2009) mission provided a breakthrough in the understanding of the solar wind, revealing high-speed streams that fill the heliospheric volume above the poles at solar minimum, how this state is disrupted at solar maximum, and how MHD turbulence and wave-particle interactions in collisionless plasma regimes differ greatly from those in the ecliptic. This mission achieved a high inclination (80 degrees) and stayed between 1.3 and 5.4 AU from the Sun. Ulysses carried plasma and fields instrumentation for characterizing the solar wind (including its particle composition). However, Ulysses suffered from the lack of remote-sensing instruments, the single point out of ecliptic in situ measurements and the large distances from the Sun.

Two of these restrictions will shortly be addressed by the ESA/NASA Solar Orbiter mission, launched in February 2020. The mission will achieve an orbital plane reaching solar latitudes of 33 degrees and will cover radial distances between ~0.28 and ~1 AU during each orbit. Besides an in-situ instrument package, Solar Orbiter also carries a comprehensive set of remote sensing instruments to probe the solar atmosphere in a variety of wavelengths. From the 30+ degree latitude vantage point, these instruments will be able to make the first detailed measurements of the fields and flows at the poles of the Sun. However, Solar Orbiter and near-Earth resources will provide a nearly global coverage of the Sun only at opposition and even then, only partially, with at most one pole being well visible and the region around the limb of the Sun being poorly observed.

To understand the full origins of all solar wind packets moving out into the heliosphere, a multi-point measurement capability must be realized with both remote sensing and in-situ data. This is necessary to understand the various mechanisms that may heat and accelerate solar wind packets from different sources, how they interact, how magnetic flux is transported throughout the heliosphere and how solar wind generation evolves with the solar cycle.

Achieving even sparse in situ coverage of the 3D solar wind is unrealistic in the near- or medium-term timeframe with progress depending on serendipitous measurements for some time to come. However, our understanding of the global solar wind would be significantly enhanced if we could achieve full remotely sensed coverage of the global solar atmosphere. This would guarantee that a complete map of source characteristics could be used in comparison to the in-situ measurements and their variations around an orbit. With that information, even a handful of in-ecliptic and high latitude measurements of the solar wind would provide a dataset capable of constraining many theories of solar wind origin, acceleration, and transport.

Firefly observations in EUV and white light from four spacecraft, two of which will be orbiting to high solar polar latitudes, in combination with in-ecliptic assets, will provide a full global view of the coronal source regions of the 3D solar wind outflow. contemporaneous in situ measurements of solar wind plasma from the four locations, combined with temporal extrapolations and modelling that will allow the determination of the latitudinal and longitudinal structure of the solar wind over relatively short time periods, support the unambiguous identification of the source regions for all sampled solar wind packets, and determine how both the ambient plasma and transient events evolve during transport to the outer heliosphere. Over extended mission lifetimes these measurements will also enable the assessment of how these influences on various solar wind regimes change with the solar cycle.

(4) Understanding the 360-degree view of global sources and transport of energetic particles through the heliosphere.

The Firefly mission will provide the first 360-degree view of global sources and transport of energetic particles. Energetic particles are a key element in understanding the impact of space weather, but how they are transported is unclear. Energetic particles can only be accelerated by electric fields. These occur as a result of rapid changes in the magnetic configuration (in flares) leading to DC or turbulent electric fields, or when particles repeatedly move across a steep gradient in the magnetic field (in shocks). There is ample observational evidence for acceleration by magnetic reconnection and (MHD) shocks, and both processes are likely important in the overall picture of solar energetic particles (SEPs), separately or possibly together (e.g. with a flare providing seed particles for further acceleration by a shock). To identify the origin of the SEPs in the corona and heliosphere requires knowledge of the time-evolving 3D structure of pre- and post-eruption magnetic fields, coordinated with in situ particle measurements. We need to determine the 3D structure of shocks stereoscopically from white-light coronagraph images and find likely sites of coronal reconnection from the 3D coronal field structure, tracing the access of particles in or near these regions to the open field. We need reliable knowledge of magnetic connectivity between the coronal or heliospheric acceleration sites and the sites where the particles are measured.

One of the important findings enabled by STEREO is the large longitudinal extent of SEP events which remains unexplained [26],[27]. It may require injection over a large range in longitudes (and latitudes) at the Sun, emphasizing the need for a 3D view of shocks. The latitudinal extent of SEP distributions is largely unknown, though Ulysses measured puzzling latitudinal dependencies of accelerated particles, possibly hinting at complex configurations of the magnetic field. The onsets of particles at, both Ulysses' high latitude as well as in the ecliptic plane were prompt, and both showed strong, field-aligned, and outward-pointing anisotropies [28]. This could be explained by shocks reaching such high latitudes or by very efficient diffusion across the interplanetary magnetic field (IMF, [29]). Both would have to occur close to the Sun to explain the observed anisotropies.

Wide-spread angular SEP events have implicated global coronal "EIT waves" [30]. However, the mapping of coronal waves is severely restricted by the current restricted vantage points, so spatial and temporal relationships with the SEPs are hard to establish unambiguously. Sometimes "EIT waves" seem to agree reasonably well with the timing of SEP injection [31], sometimes not [32] (see Figure 3). The wave speed depends on the coronal field and density, which vary as a function of location on the disk and altitude in the corona. With the multi-vantage point EUV imaging and WL coronagraph measurements from Firefly, the propagation of EIT waves can be properly tracked through the corona to identify likely times and locations of SEP injection.

Moving out into the heliosphere, particle transport is governed by the properties of the heliospheric magnetic field, which changes at all spatial-temporal scales: solar rotation, features on the solar surface (coronal holes and their boundaries), reconnection, flux tubes, turbulence, all the way down to time scales typical of the local plasma. Energetic particles average over a large spatial volume due to their gyro-motion and motion along their trajectory, but scatter off the IMF, which is loosely described as a diffusive process e.g. [27]. Evidence that this is the dominant effect in explaining SEP observations at Ulysses [29] does not explain the substantial observed anisotropies [28]. Because active regions are concentrated along low-to-mid-latitude regions, a polar/3D view of the Sun and heliosphere would allow discrimination between the three mechanisms affecting solar particle acceleration and transport: the extent of coronal shock and their relation to EIT waves, the role of flares in providing the seed population, and diffusion across the IMF.

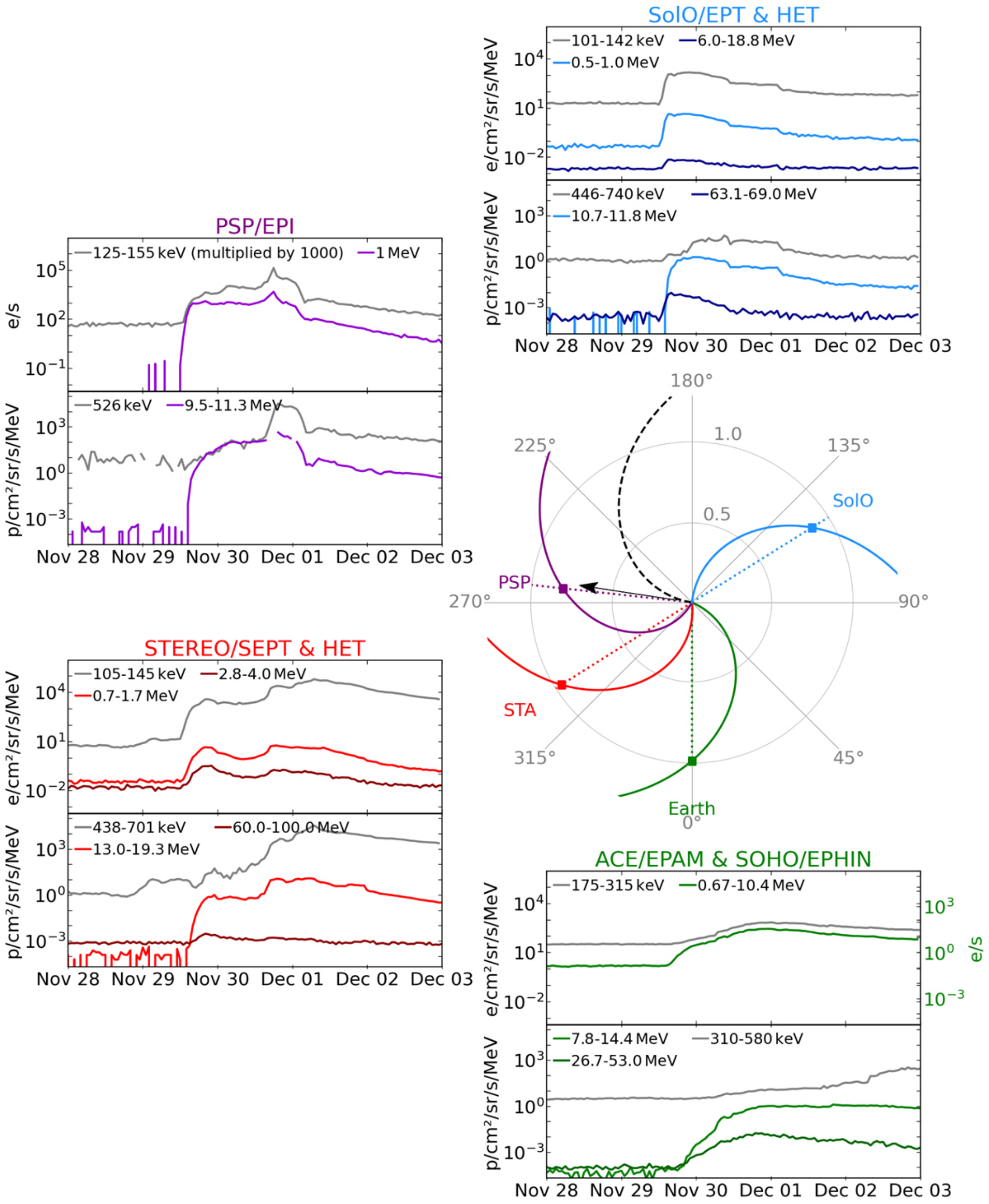

Figure 3: An example of the importance of multi-viewpoint measurements for SEPs – the large extent of the event on 29 November 2020 is clear [32]

Summary*:*

In this white paper, scientists from Europe and Japan describe how their scientific interests align with those of the Firefly mission described in the white paper by Nour Raouafi. By providing a 4 π coverage of the Sun with in-situ and a suite of remote sensing instruments, Firefly will provide deep new insights that will answer a whole range of big open questions in solar and heliospheric physics as described in this white paper that are currently unobtainable because of our restricted views.

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