Discovering a magnetized plasma ocean of mega tsunamis above the surface of the Sun

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Abstract

The earthquake that generated a tsunami in the Indian ocean on 26th Dec. 2004 was the second most powerful one ever recorded. However, this was merely a droplet in the ocean compared with the tsunamis we have discovered and modelled in the solar atmosphere. Wave driven phenomena are fundamental for the energetics and dynamism of the atmosphere of the Sun, as well as, being important in the context of the Sun-Earth connection. Wave-driven spicular jets form the origins of the fast solar wind which impacts upon Earth's atmosphere causing serious geomagnetic storms and determine Space Weather. Here we present our discovery of a hot magnetized plasma ocean of mega tsunamis in the lower solar atmosphere, named as Transition Region Quakes (TRQs). These TRQs are localized to the Transition Region (TR), 2000 km above the visible solar surface. The TR is a sharp transition in temperature and density between the relatively cool and dense lower solar chromosphere (2 x 10^4 K) and the very hot upper corona (1-15 x 10^6 K). The long-standing coronal heating enigma, one of the greatest puzzles of modern science and astrophysics, may be addressed by firstly understanding the processes which power its lower base, i.e., the TR itself. To understand the wave processes of the solar atmosphere we used a combined approach of advanced numerical modelling, via a supercomputer Iceberg in Sheffield, as well as joint satellite observations involving more than one spacecraft simultaneously.

Solar Jets

Jet-like spicules are the most abundant features in the lower solar atmosphere [1,3,7,8]. Wave-driven (type-I) spicules are considered to be important in the energizing processes which heat the TR [4,5,10]. Type-I spicules result from photospheric *p*-mode (acoustic wave) leakage along magnetic field lines rooted in the inter-network of convective cells at the surface [2].

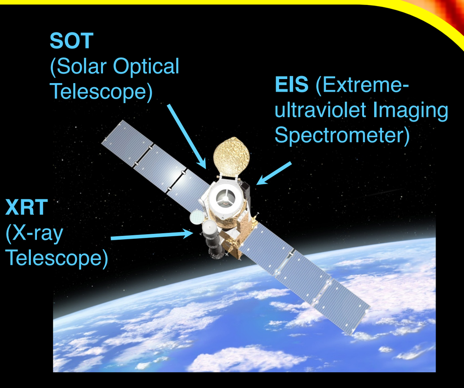


Fig. 1 The recent launch (late 2006) of the *Hinode* (meaning, 'Sunrise') space observatory with 3 instruments onboard, (EIS, SOT and XRT) allows for observations over a wide temperature range with high spatial and temporal resolution.

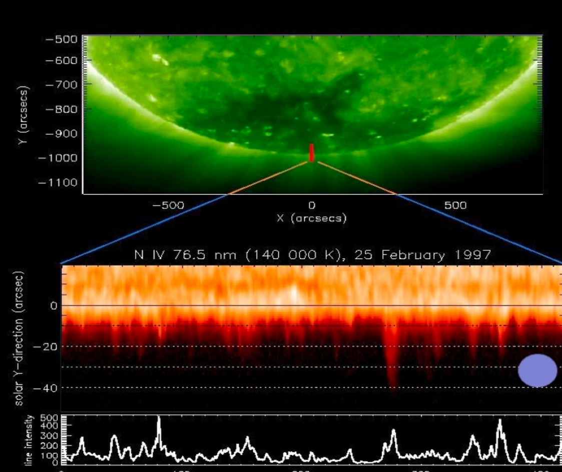


Fig. 2 Solar spectroscopy can diagnose the plasma properties of the different layers in the solar atmosphere. The narrow slit (1 arcsec = 715 km) of the SoHO/SUMER instrument is pointed towards the limb of a polar coronal hole (red line) and records 'time series' data in different spectral emission lines (*middle*). Spicule jets of ~1500 km widths, are most visible at the solar limb [9], extend from 7,000 - 10,000 km, with rise velocities of 25 km/s [8].

It has been shown that spicular *p*-modes (with 5-min oscillations) contain sufficient power to travel, as transient plasma jets, through the temperature minimum in the chromosphere [5, 6] and puncture the TR. However, the impact of the spicular wave-train on the TR and subsequent wave energy dissipation has not been understood until now.

Mega Tsunami Observations

We report the initial appearance of a jet at the Sun disk centre on 5th March 2007 (18:12 UT) (see Fig. 3). The jet event is clearly detected with EIS (40x512″ slot) at lower TR temperatures (*He* II *256.32*; line formation =$10^{4.7}$ K) and STEREO/SECCHI (*He* II *304*; $10^{4.9}$ K).

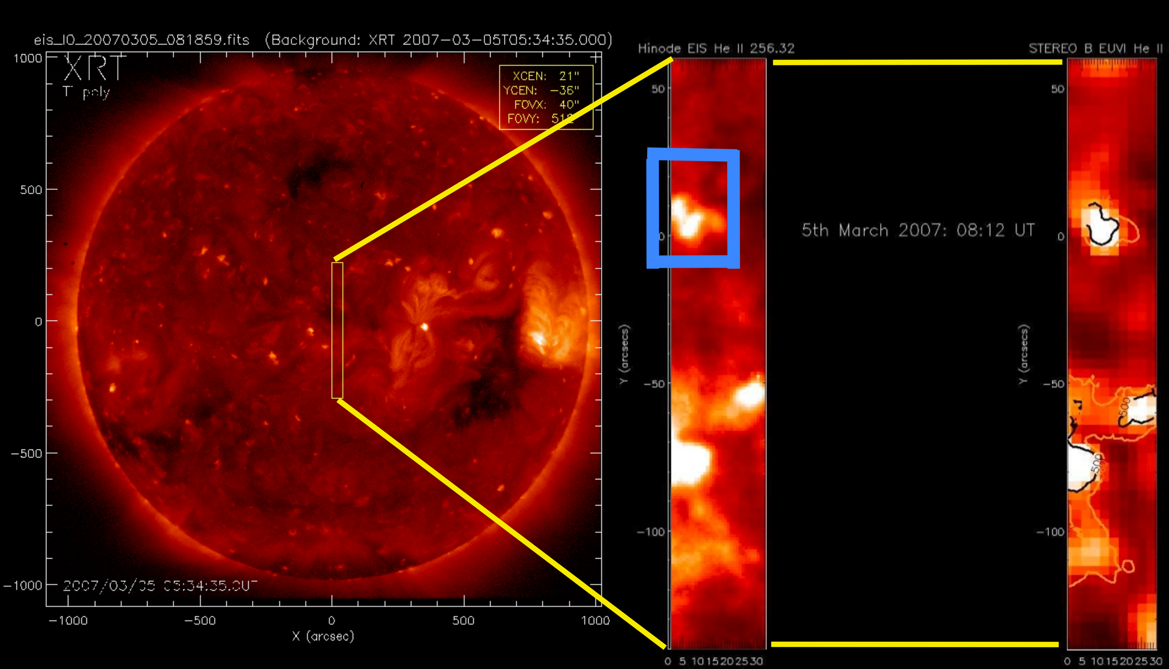
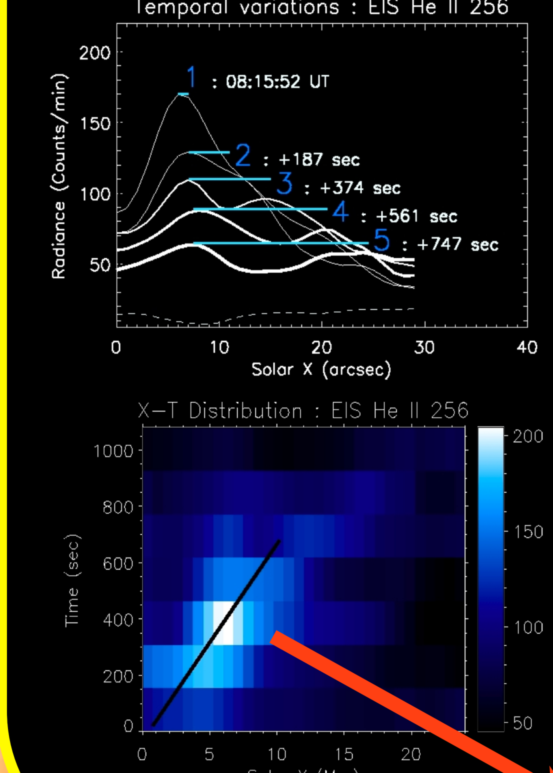


Fig. 3 Full-disk *Hinode*/XRT (X-Ray Telescope: Ti_poly filter) observation at the time of the event (left). The centered yellow box is the EIS FOV. The *He* II *256.32* emission line of EIS (middle) and *He* II *304* of STEREO / SECCHI (right) reveal the same features associated with the TR. The jet is bounded by the blue box.

Fig. 4 (right) reveals the plasma jet formation and projection (red arrow) at the TR in EIS and the response of the atmosphere at different heights above the surface, via a multi-instrument observational approach. The EIS FOV also reveals, for the first time, the formation of a horizontal quake-like ring structure (solid white contour) at the TR which appears ~3 min after the rise of the jet. The quake ring then propagates along the TR (dashed white contour). The top left plot in Fig. 4 presents the evolution (markers 1 to 5) of the wave front as measured by taking cross-cuts of the data in EIS He II *256.32*. TRQ wave fronts have almost six times the range (30,000 km) compared with the Indian ocean tsunami and propagate at an incredible 12 km/s (26,840 miles/hour), making the total range of this mega tsunami twice the diameter of the Earth at the equator. A time-distance analysis (X-T plot; bottom left Fig. 4) is used to determine the velocity of propagating waves.



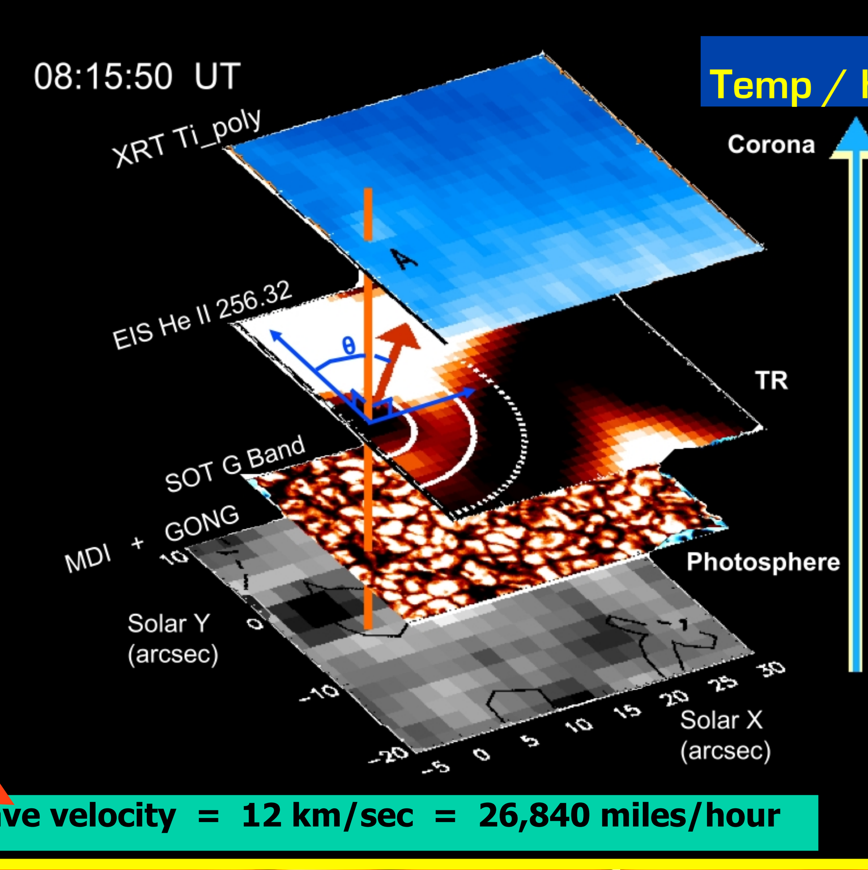
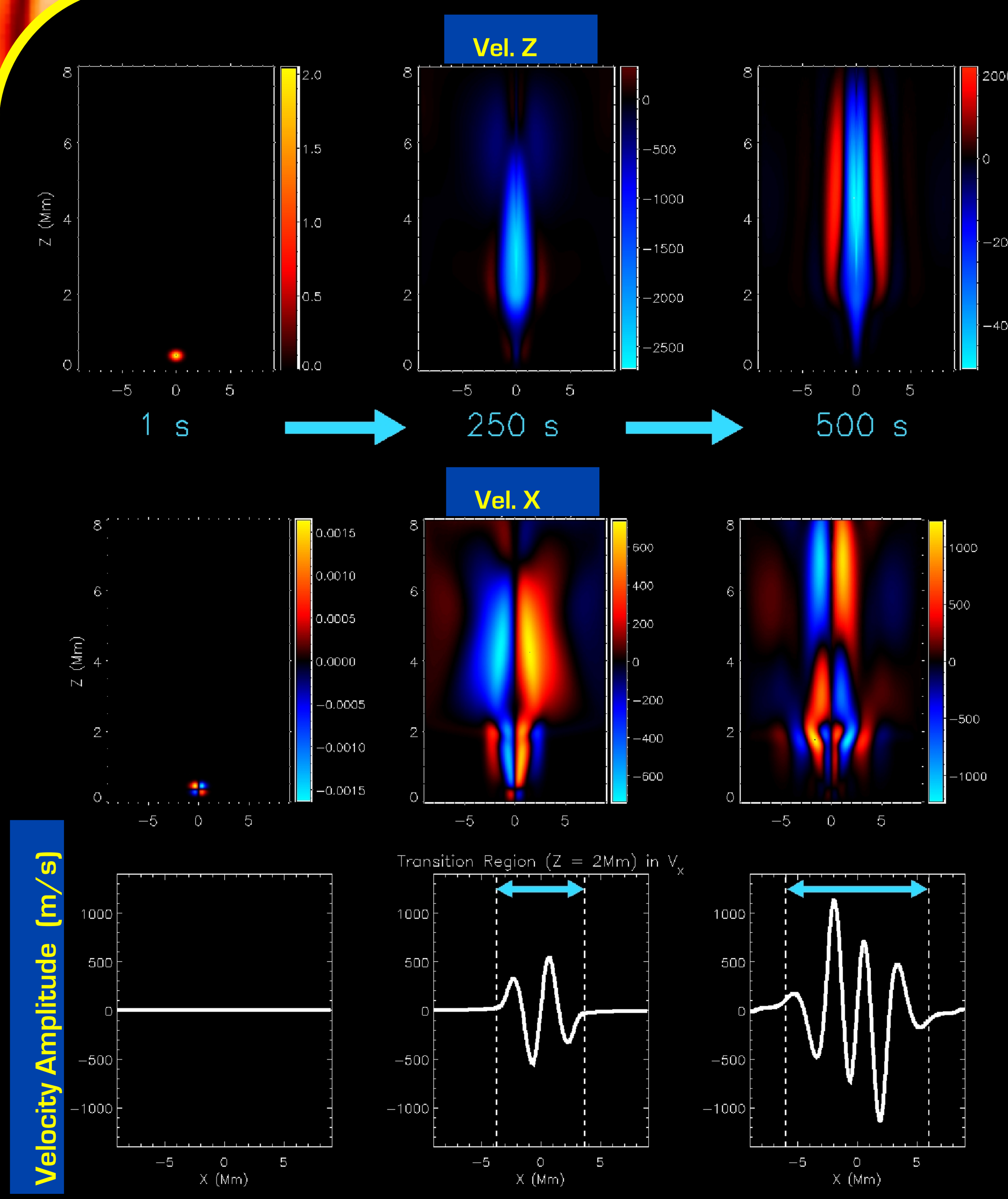


Fig. 4 (Right) Co-aligned observations of the blue boxed region at 18:15:50 UT with (from top to bottom) XRT, EIS, SOT (BFI Broadband Filter Imager; *CH* I 4305 line emission (G Band); 0.0544″/ px spatial res.; 6 s cadence), SoHO / MDI (Michaelson Doppler Imager) and a GONG (Global Oscillations Network Group) magneto-gram (black contours).

Numerical Simulations



Never before has wave energy coupling through a real 3D solar atmosphere, to reveal structure, been simulated. The snapshots of SAC (Sheffield Advanced Code) simulation, from left to right in Fig. 5, show the advancing solution of plasma velocity components (V_Z - top and V_X- middle) in a model solar atmosphere from 0-8,000 km in Solar Z (height) and -10 to 10,000 km in Solar X. Here we highlight the *p*-mode propagation from the surface through the solar chromosphere, TR (Z = 2,000 km) and corona, driven by a smoothed Gaussian sinusoidal ellipsoid. Spicular plasma jets (V_Z) which oscillate with 5 min periodicity, as expected, are found. These jets reach a height of ~8,000 km. We have also found, for the first time, quakes at the TR in V_X, i.e. TRQs. The TRQ amplification and propagation is described though the data cross-cuts (bottom, Fig. 5) in V_X. The TRQ range is 15,000 km after 500 s.

Fig. 5 Snapshots of 2.5D (x, y=constant, z) MHD (magnetohydrodynamic) simulation of a magnetically embedded (field strength of 4 Gauss) and gravitationally stratified stable solar atmosphere are plotted. The simulation solves for 8 variables (V_Z, V_X, B_Z, B_X, B_Y, *e*, *ρ*) numerically, due to the highly non-linear nature of the MHD equations, which are described by the Maxwell equations of electromagnetism and the Navier-Stokes equation of fluid dynamics. Magnetohydrostatic equilibrium is maintained throughout the integration in time and space. Photospheric sinusoidal pulsations (300 s periodicity), mimicking *p*-mode waves, are driven at the solar surface through to 8,000 km above the solar surface.

TRQs form as a consequence of upward propelling spicular wave trains that repeatedly punctures and energizes the TR. The TRQ, i.e. circular magneto-acoustic surface gravity wave, radially fans outwards from the locii where the ubiquitous spicular plasma columns impinge the TR, and become guided by the natural density and temp. gradient of the TR, analogous to seismic waves (tsunami's) formed at Earth's surface during an earthquake. Our model to describe this process is illustrated in Fig. 6.

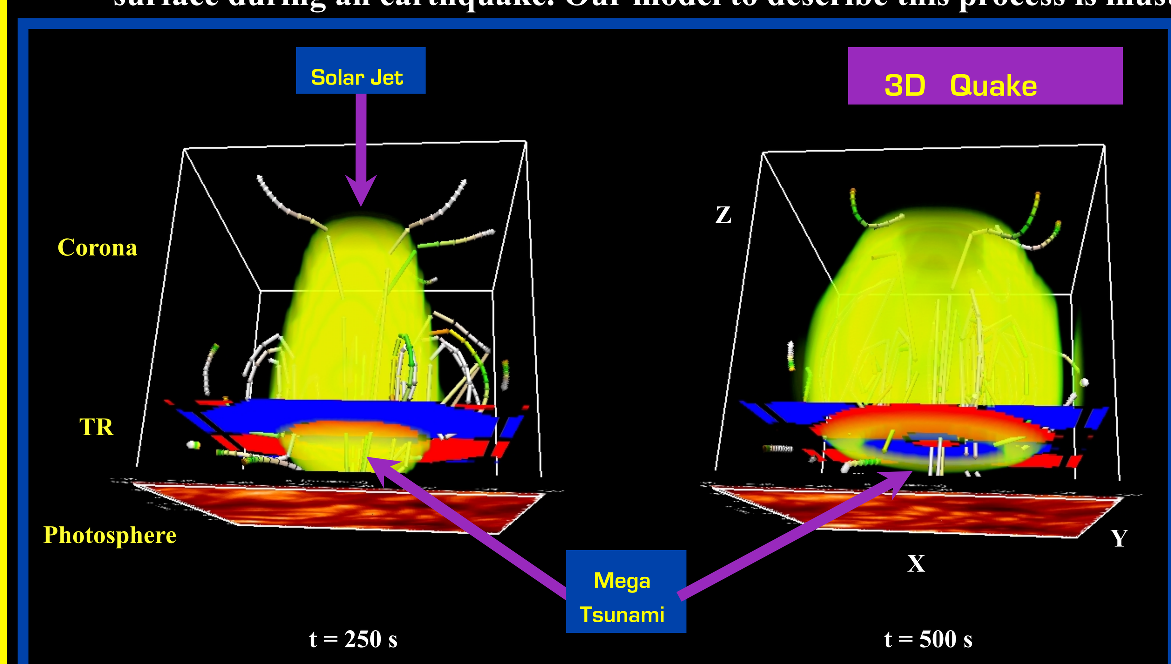


Fig. 8 We present two snapshots at *t* = 250 s and 500 s of the TRQ (mega tsunami) wave ring formation from the output of a 3D MHD simulation. The dimensions of the domain are 4 Mm x 4 Mm x 8 Mm in *x*, *y* and *z* respectively. The yellow spicular structure is a visualization of V_Z, white lines are the total *V* component and the blue/red distribution is an isosurface of the TR.

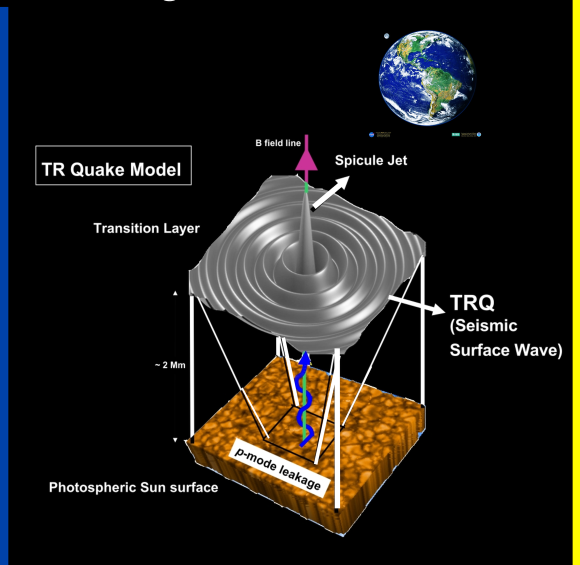


Fig. 6 Cartoon of TRQ depicting the physical mechanism leading to formation of a mega tsunami at the TR. The Earth is plotted to indicate the scales involved.

Impact on Solar Atmosphere

We compare the observations of the TRQ directly with our spicule simulations. The TRQ has an amplitude of 500 km. This reveals a wave front ~20,000 times greater than tsunami breaking waves of the Indian ocean (30 m). The consequences of wave energy dumping in the form of mega tsunamis is significant when one considers the energy balance of the TR.

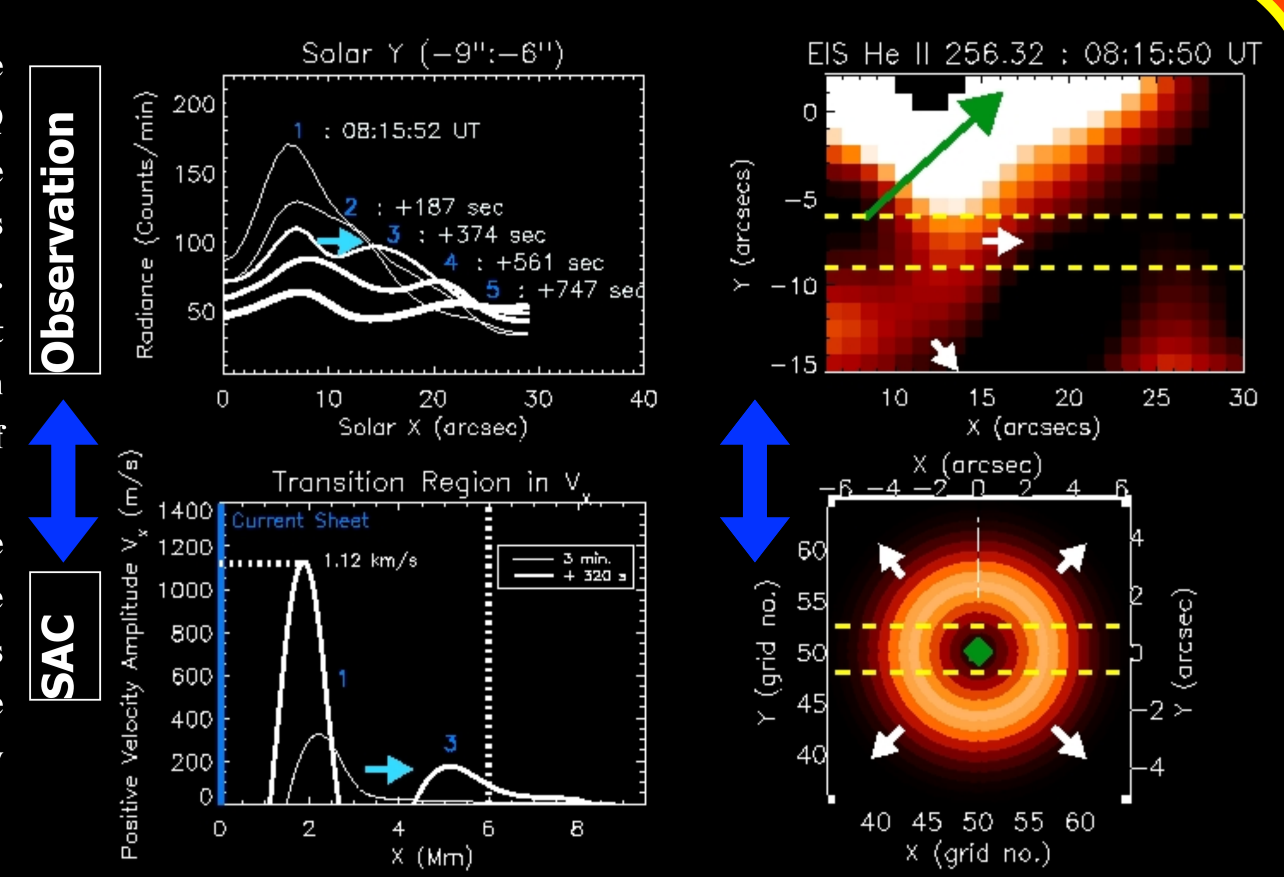


Fig. 9 Comparing the observed TRQ wave formation with the simulated TRQ (top and bottom left). In the bottom left the evolution of the simulated data cross-cuts (markers 1 to 3) **match directly** with the observed wave propagation (top right) in time between markers 1 and 3 of wave damping and velocity. Likewise the geometry of the wave ring at marker 1 is presented (top and bottom right) and matched.

Radiative energy losses at the TR (190 W/m^2) must be replenished by the wave energy transfer from below, along with emission via explosive events. The max. TRQ velocity amplitude in V_X (bottom left Fig. 9) is 1.12 *km/s*. With a propagation velocity of 12 *km/s* the wave energy dumping in a mega tsunami event is 1.2 W/m^2 . This is equivalent to 1 million billion joules (16 hiroshima nuclear explosions) over the mega tsunami range. We have quantified for the first time [12] the extent of wave energy transfer into the outer atmosphere of the Sun as a result of spicule generated TRQs.

Conclusion

The TRQ model presented here is the first proposed viable mechanism in solar physics in understanding how the energy budget of the global TR could be maintained and partially replenished when wave transmission from the photosphere is considered. Each spicule can generate a mega tsunami wave at the TR and there is estimated to be ~60,000 spicule events per second. Hence, each mega tsunami, with an average range of 30,000 km, could accumulate in delivering energy to over 2/3 of the Sun surface area. We have discovered that the TR could be envisaged as a hot, torrential, magnetized plasma ocean of mega tsunami interactions, continuously accumulating and energizing an area 55 million times larger than the Indian ocean.

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