Faster than the blink of an eye

Francis P Keenan, Mihalis Mathioudakis and David B Jess discuss high-speed observations of the solar atmosphere made possible with ROSA, the "Rapid Oscillations in the Solar Atmosphere" imager built by Queen's University Belfast.

The Sun is the most important astronomical object for humanity; solar atmospheric activity drives "space weather" and has a profound effect on, among other things, our climate and communications. It is important to understand such activity, with the ultimate aim of predicting events such as solar flares, which can be a hazard to satellites and even astronauts. To investigate, and ultimately predict, solar activity, we need to observe and model physical processes in the solar atmosphere on their intrinsic scales. It is vital to link small-scale processes with the resultant large-scale phenomena such as flares, prominences and coronal mass ejections.

In addition, the Sun offers a unique physics laboratory where the interactions of the plasma and magnetic field can be studied in detail, and the understanding gained applied to other astrophysical sources such as accretion discs and magnetized jets. While we are only able to catch glimpses of these processes and phenomena in other objects, the Sun allows us to study them at an unprecedented level of detail.

High-cadence (i.e. high time resolution) observations of astronomical sources is a growing field within astrophysics, and there is a clear need for such data for the Sun. Many solar research topics, in particular those related to the dynamic Sun and the heating of its atmosphere, involve the observation and modelling of wave phenomena and explosive events over very short timescales. Indeed, hydrodynamic models predict that significant solar atmospheric changes can occur over timescales as short as 0.1 s or less (Allred *et al.* 2005) – much faster than even the blink of an eye (about 0.4 s).

For the Sun, high-cadence observations are also important for *post-facto* image reconstruction (PFIR) techniques, which involve the processing of an extensive collection of images in order to produce a single frame at diffraction-limited resolution. These short-exposure images must be accumulated over timescales sufficiently small so that atmospheric turbulence is effectively "frozen out", and solar features remain unchanged. As a result, with PFIR it is possible to obtain better spatial resolution with ground-based solar telescopes than with space-based instruments, as a result of the (generally) larger aperture of the former.

1: ROSA is installed on the Richard B Dunn Solar Telescope (DST) at the National Solar Observatory, Sacramento Peak, New Mexico. Although the tower of the DST rises 41.5 m above ground level, another 67 m of the telescope lies out of sight underground. (NOAO/AURA/NSF)

ROSA

In 2006 we obtained funding from Queen's University Belfast (QUB) and PPARC to construct a new solar imager, called Rapid Oscillations in the Solar Atmosphere (ROSA), with the aim of obtaining high-cadence, diffraction-limited images of the Sun in multiple wavebands. ROSA was constructed at QUB during 2007 and 2008, with the major component being the cameras, which are iXon+ Electron Multiplying CCDs from Andor Technology of Belfast. The electron multiplying feature of this CCD is very important for observations involving very short exposures through narrow-band filters, off-limb regions or for high-resolution spectroscopy. It contains a 1004×1002-pixel frame transfer sensor, which allows charge to be multiplied on the sensor before it is read out, while utilizing its full quantum efficiency performance. The full chip can operate at a frame rate of up to 31 frames per second (fps), increasing to 200 fps for a 125×125-pixel window. This was the first time this type of CCD had been employed in a solar instrument.

Each ROSA camera has its own dedicated high-speed server that controls data acquisition and storage. The servers are Dell PowerEdge 2900 dual-core Xeon units, each with 4 GB RAM and over 1 TB of on-board storage. To achieve sustained frame rates and prevent data corruption, each ROSA server consists of eight high-speed (15 000 rpm) hard drives, running in a RAID 0 configuration to boost available storage. The six servers are mounted in two wheeled-rack enclosures, allowing the entire system to be repositioned easily. All the ROSA cameras are triggered via a precision control unit (otherwise called the "sync" box), which provides independent pulses to each camera to control the frame acquisition at preset trigger rates. This is a vital component of ROSA – all cameras are synchronized to an accuracy of 50 μs, so that images from one CCD may be reliably compared with those obtained by others. As a result, the multiple wavebands of ROSA permit observations from up to six different heights in the solar atmosphere, simultaneously. Effectively the whole atmosphere from the low photosphere to the upper chromosphere can be observed and analysed as one coupled system.

Running a sustained frame rate of 30 fps in all six ROSA cameras produces approximately 1.3 TB of data every hour. The data are written into FITS format, incorporating a header and multiple image extensions. Detailed information related to the observing sequence are written in the main FITS header, and include descriptions of both the CCD and observing parameters, as well as the acquisition start time.

Once ROSA was constructed it underwent extensive laboratory testing at QUB, before being relocated to the Dunn Solar Telescope (DST; see figure 1) at the US National Solar Observatory (NSO) at Sacramento Peak for commissioning late in 2008. The commissioning was completed in early 2009, with the system working to full specifications (Jess *et al.* 2010). It is now installed as a common-user instrument on the DST, where it provides both unprecedented time resolution (5 ms) and diffraction-limited spatial resolution with the application of PFIR (better than 0.1 arcseconds).

Several ROSA images are shown in figures 2–4, while further technical specifications and additional images may be found in Jess *et al.* (2010) and on the ROSA website (http://star.pst.qub.ac.uk/rosa).

There are numerous research areas of major importance in solar physics that are ideally suited to exploit the unique capabilities of ROSA. Some examples are outlined below.

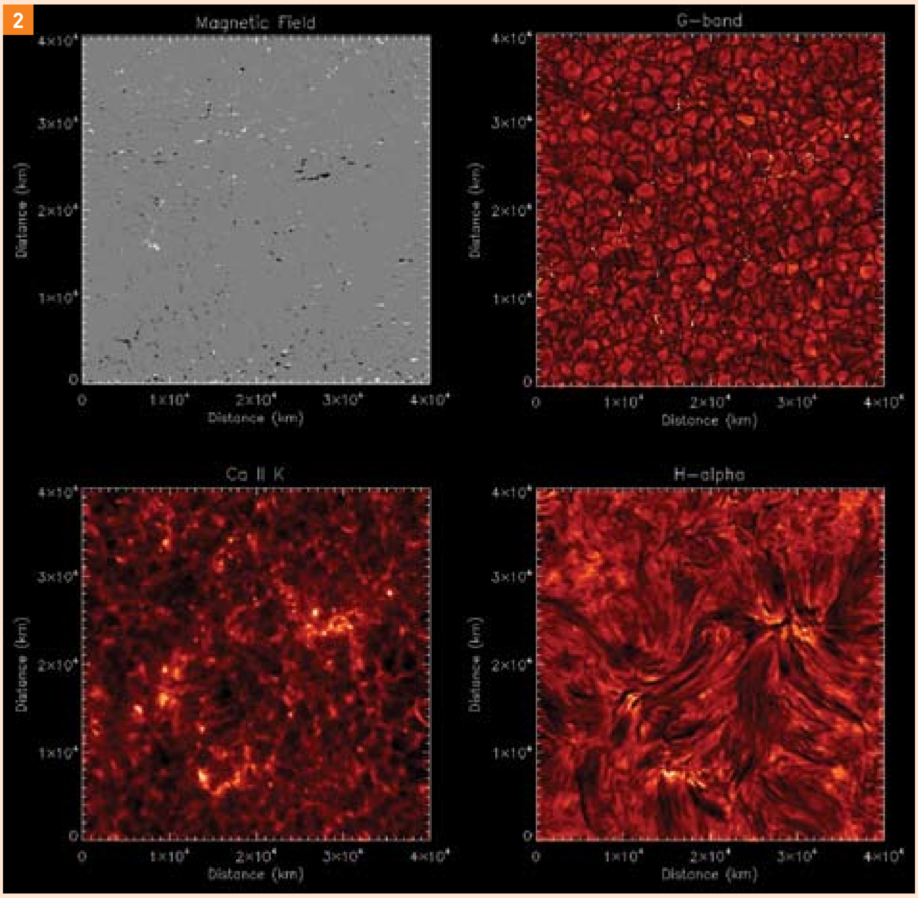
The explosive Sun

Solar flares vary enormously in magnitude and duration, from rare large X-class flares to common micro-flares and other sub-arcsecond resolution small explosive events. During flares there is a rapid energy transfer between the corona, chromosphere and photosphere through non-thermal electron beams, radiation, conduction and mass motions. The intermittent nature of the non-thermal electrons can result in very short timescale variations in the emission from the chromosphere and corona. These variations arise from a combination of the energy/ionization imbalance and chromospheric condensation, and are determined by the intensity of the non-thermal flux deposited in the lower atmosphere. Our understanding of flares and other explosive solar events will benefit tremendously from the high-cadence capabilities of ROSA, particularly when combined with space-borne instruments such as RHESSI, Hinode and SDO.

Wave energy transport in the lower solar atmosphere

The solar photosphere and chromosphere comprise a complex arrangement of magnetic and non-magnetic regions. Acoustic waves, developing into shocks, may provide sufficient energy for heating the field-free regions, but the chromospheric network requires additional heating of magnetic origin. One possible candidate for this is turbulent motion of the convection zone, which drives the velocities in the photosphere, leading to the generation of transverse/MHD waves. These can couple to longitudinal waves, which can then shock and transfer the energy to the surrounding plasma. Magnetic structures in the lower atmosphere act as waveguides for the propagation of perturbations to greater atmospheric heights. The link between the various regions of the solar atmosphere can be explored by studying oscillatory signatures as a function of height and temperature (Erdelyi 2006). In this regard, the synchronous ROSA cameras will be vital in providing multi-waveband (i.e. multi-height) observations, and accurately tracking the oscillatory power of waves in the photosphere and chromosphere. Although the waves in question typically have periods of between 100 and 1000 seconds, higher-cadence observations provide the opportunity to freeze out and remove atmospheric seeing, allowing spatial sampling of better than 0.1 arcseconds/pixel. Because all six CCDs in ROSA can be synchronized by the same trigger, these multi-wavelength observations can be obtained with the same time stamp.

IMAGES OF THE SOLAR ATMOSPHERE COLLECTED BY ROSA



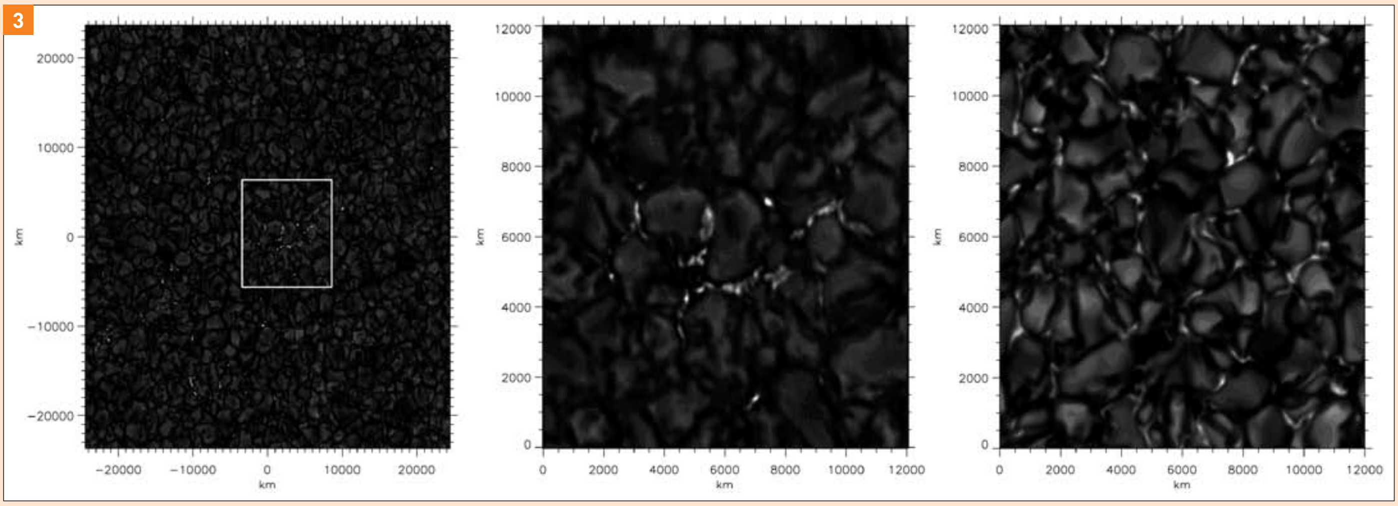
Solar magnetic fields at high cadence

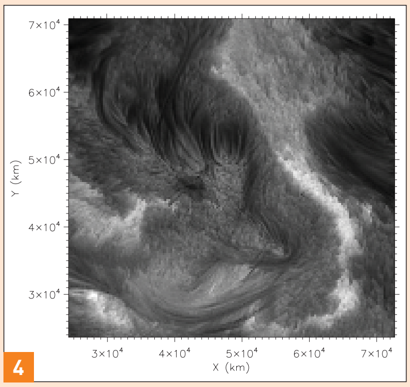
Upflows and downflows at the top of the solar convection zone continually rearrange the magnetic field, allowing it to form various structures, and the dynamic nature of this field is responsible for solar activity. It can be brought up in granules, but is then moved to the intergranular lanes where it is compressed and becomes sufficiently strong to be detected in features such as the magnetic bright points (MBPs). The small-scale field, combined with the photospheric motions, plays an important role in the transport of energy to the outer atmosphere. In recent years, high-spatial-resolution observations have revealed that the small-scale magnetic flux concentrations are the building blocks for the fields associated with larger magnetic structures (Steiner 2005). Models of magnetoconvection show that in the lower chromosphere there is a continuous rearrangement of the magnetic flux over timescales of less than 1 minute, significantly shorter than those found for the convection zone. Furthermore, during flares, the longitudinal magnetic field in the photosphere can change at a rate of tens of Gauss per minute (Sudol and Harvey 2005). The superior sensitivity provided by the electron multiplying feature of the ROSA CCDs will allow measurements of longitudinal magnetic fields at high cadence.

ROSA upgrades

Although the system has been fully operational to its original specifications since 2009, ROSA has recently undergone several upgrades, and more are planned during 2011 and 2012. As a result of extensive testing during 2010, ROSA imaging may now be undertaken simultaneously with imaging spectroscopy via the IBIS instrument (Interferometric Bidimensional Spectrometer; Cavallini 2006). Spectral lines that may be investigated with IBIS include Na I D_1 589.6 nm, H-α 656.3 nm, Fe I 709.0 nm, Fe II 722.4 nm and Ca II 854.2 nm. Simultaneous IBIS imaging can complement ROSA observations through the determination of Doppler maps with a velocity resolution as high as 60 m s^{-1}.

During 2010 a Royal Society research grant was awarded to buy a new breed of CCD camera with quantum efficiencies exceeding 95% in the red portion of the optical spectrum. This new high-efficiency Andor iXon$^+$ camera will enable shorter exposure times (and therefore higher-cadence imaging) in sections of the optical spectrum where deep absorption lines are present





2 (Left): A portion of the solar surface observed simultaneously with four ROSA cameras. The images reflect heights of between 50 and 2000 km above the solar surface. The smallest structures that can be resolved have dimensions of 100 km and are associated with strong magnetic field concentrations. The bubbling appearance of the G-band (430.5 nm) images is a result of hot gas rising and expanding, while reversed granulation is visible as a web-like structure through the Ca II K 393.3 nm filter. Bright points correspond to areas of intense magnetic field, which expand as they rise from the surface.

3 (Above): (Left): A 50000×50000 km region of the solar photosphere imaged in the G-band (430.5 nm) with ROSA. (Middle): A 12000×12000 km expanded portion of the central part of the image on the left. (Right): A theoretical 12000×12000 km G-band image, calculated for an average magnetic field strength of 200 G. Note the excellent agreement with the ROSA observations in the middle figure.

4 (Right): An H-α image of an M-class solar flare captured by ROSA.

(e.g. H-α 656.3 nm and Ca II 854.2 nm). It is anticipated that this new camera will be merged with the existing system during late 2011, providing a seventh ROSA science channel.

Running at a rate of 30 fps in all six ROSA cameras produces approximately 10 TB of data during a typical observing day of eight hours – extremely large data rates and volumes. As a direct result, the on-board storage capacity of ROSA has recently been upgraded to accommodate such large data volumes. With over 12 TB of storage available, it is now possible to observe the Sun continually without fear of running out of disk space. Once data have been acquired, there are two available options to transfer the results to external media for transport back to the observer's institute. These include the use of LTO3 tapes and/or hard disks. With the continual decrease in the cost of hard disks, this is the most commonly used method of data backup and transport. Users can utilize the provided docking stations to connect their hard disks to ROSA and, following an upgrade in 2010, eSATA connectivity is now available to maximize data transfer rates.

Applying for time to use ROSA

As noted previously, ROSA is now a common-user instrument on the DST. Observing time on this facility is allocated by the NSO Telescope Allocation Committee via a competitive proposal process. There are four observing periods per year (January–March, April–June, July–September, October–December), with proposals due typically six weeks in advance of the start of the observing period. As part of the agreement to host ROSA at the DST, a minimum of 20 days per year of observing time on the DST is reserved for UK-led proposals.

To help the UK community exploit ROSA, both as a stand-alone facility and for joint programmes with satellite-based instruments, STFC has funded a UK support facility for ROSA at QUB. Specifically, we provide:

- Support for proposal preparation, including advice on ROSA capabilities and performance. We also provide advice on other NSO instrumentation that may be used in conjunction with ROSA, such as the Fabry–Perots on the DST.
- Observing support at the DST for the full duration of the observing run.
- All ROSA data reduction, including the application of PFIR techniques to provide proposers with diffraction-limited data ready for analysis. Alternatively, for groups with experience in the reduction of ground-based solar imaging data, we can provide a complete set of ROSA pipeline reduction software for installation at the proposer's institute.
- Access to a range of software tools that may be used for the automated detection and tracking of solar features at the diffraction limit.
- A fully maintained archive of all reduced ROSA data.

Several groups have already won time on ROSA, and indeed to date the allocation of time to UK-led proposals has been much greater than the minimum 20 days per year, because of the quality of the proposals submitted.

We believe that ROSA is a unique facility for the UK solar physics community, particularly for high temporal and spatial resolution studies of the dynamic solar atmosphere. The guaranteed time on the DST for the UK community provides low-cost, formal access to the world's leading ground-based facility for studies of the solar atmosphere. It is important that this observing time is fully exploited.

If you are interested in using ROSA for your research programmes, or even if you just want more information, please email Prof. Mihalis Mathioudakis at QUB in the first instance (m.mathioudakis@qub.ac.uk). ●

Further reading

ROSA website http://star.pst.qub.ac.uk/rosa

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