

The Irkutsk Barium filter for narrow-band wide-field high-resolution solar images at the Dutch Open Telescope

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ABSTRACT

A wide-field birefringent filter for the barium II line at 455.4nm is developed in Irkutsk. The Barium line is excellent for Doppler-shift measurements because of low thermal line-broadening and steep flanks of the line profile. The filter width is 0.008nm and the filter is tunable over 0.4nm through the whole line and far enough in the neighboring regions. A fast tuning system with servomotor is developed at the Dutch Open Telescope (DOT). Observations are done in speckle mode with 10 images per second and Keller-VonDerLühe reconstruction using synchronous images of a nearby blue-continuum channel at 450.5nm. Simultaneous observation of several line positions, typically 3 or 5, are made with this combination of fast tuning and speckle. All polarizers are birefringent prisms which largely reduced the light loss compared to polarizing sheets. The advantage of this filter over Fabry-Perot filters is its wide field due to a large permitted entrance angle and no need of polishing extremely precise surfaces. The BaII observations at the DOT occur simultaneously with those of a fast-tunable birefringent H-alpha filter. This gives the unique possibility of simultaneous speckle-reconstructed observations of velocities in photosphere (BaII) and chromosphere (H-alpha).

Keywords: Birefringent filters, Barium filter, Fast-tunable filters, Speckle reconstruction Keller-VonDerLühe, Doppler shift, Velocities Solar Surface, Photospheric observations, Photospheric and Chromospheric velocities

1. INTRODUCTION

An important advantage of the Barium II 455.4 resonance line is barium being a very heavy atom, which makes the thermal contribution to the Doppler width of the spectral line small. Moreover, at high angular resolution much of the solar fine structure that used to be parameterized as ‘non-thermal microturbulence’ in classical plane-parallel line-formation modeling, no longer acts as line broadening, but actually is resolved, which makes the non-thermal contribution to the line broadening small as well. This results in a line with steep wings, giving a large Doppler sensitivity. In addition, the Ba II 455.4 nm line is split into 14 isotope and hyperfine structure components¹. In a spatially averaged solar spectrum the line shows a wide asymmetric core. In highly resolved observations the line wings steepen, while the core preserves its width. All together, this makes the Barium resonance line very suitable for Doppler measurements with a spectral filter which does not have to be extremely small.

This peculiarity of barium had already been recognized in the seventies and at Irkutsk a development started of a tunable wide-field birefringent filter, especially dedicated to the Ba II resonance line^{2,3}. Due to tough contact possibilities at that time, it was not before the year 2000 that this unique filter had its first try-out at a high-resolution telescope, the former Swedish Vacuum Solar Telescope (SVST) at a place with the required excellent daytime seeing conditions, the Observatorio del Roque de los Muchachos (ORM) on the Canary Island La Palma. This test was very successful⁴ and further use was planned as part of a multi-wavelength speckle imaging system at the Dutch Open Telescope (DOT)^{5,6,7}, neighbour of the SVST at ORM on La Palma.

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An additional plan was to develop a magnetograph based on a full Stokes polarimeter in front of the Ba filter^{8,9}. However, further tests at the DOT and at the new Swedish Solar Telescope (SST)¹⁰ were no longer successful due to a much lower light throughput of the Ba filter than expected. A severely darkening of the oil in the filter turned out to be the reason. In the ensuing section we will describe how this problem was solved and in which way the Ba filter was made suitable for fast and continuous tuning by a servo-motor system. This system provides the opportunity to make movies of Doppler maps. Furthermore, we will discuss the optical system of the Ba filter, the tuning mechanics and first solar observational results, followed by plans for future work.

2. DESCRIPTION OF THE BARIUM FILTER

The Barium filter consists of 12 birefringent crystal stages, of which six with quartz plates and six with calcite plates¹¹. The quartz with its lower birefringence is used for the rough wavelength selection, the calcite with high birefringence for the narrow-band selection. Each quartz stage is combined with a calcite stage to a birefringent split element of the Evans design¹¹. Consequently, only 7 polarizers are required around the six split elements.

All polarizers are calcite wedges connected to glass wedges. One polarization direction goes straight through, the other is deflected and absorbed by the black stray-light diaphragms. These birefringent polarizers have a higher throughput than absorption foil polarizers.

All stages, calcite and quartz, each consist of two crystal plates providing wide field elements with low change of the retardance with increasing angle of light incidence. In addition, the calcite stages are tunable by the rotation of a half-wave plate between the two wide-field component plates, which are covered by quarter-wave plates with vibration directions, rotated by 45° with respect to the vibration directions of the crystal plates¹¹.

Originally, the filter was designed for the Barium 455.4 nm line in addition to the H β 486.1 nm line. However, the quartz stages are not tunable and, consequently, for the H β line unwished neighbouring transmission peaks are present. To suppress these peaks two additional single crystal-plate stages were added. Presently, these stages are not in use in order to maximize the transmission of the filter for use in the Barium line, which is of primary scientific interest.

Five of the six calcite stages have the usual increasing steps of thickness of a factor 2, double plate sets for wide field of 2×1.62 , 3.25, 6.51, 13.02 and 26.03 mm thickness. The sixth stage is a contrast element with plate thickness of 2×30.10 mm, which determines the width of the filter of 0.008 nm. The stages with thickness-increasing steps of a factor 2 have gear drives with an increasing velocity in steps of a factor 2 for the rotation of the half-wave plates. The drive between the half-wave plates of the stages with 26.03 and 30.10 mm thick plates has an increase of velocity proportional to the ratio of these thicknesses. All the stages have been aligned to get maximum transmission for the Barium line using a high-resolution spectrograph and a Barium spectral lamp at the laboratory at Irkutsk. The drives have been coupled in this aligned position. The gear system is driven on the shaft which drives the stage with the 26.03 mm plates, hence the nearly fastest shaft.

Originally, the tuning of the filter was done with a hand wheel on this shaft. The first test at the SVST⁴ was executed with this hand tuning. However, production of Doppler-velocity movies requires continual tuning of the filter synchronized with the camera exposures. For this purpose, a servomotor system is developed, see Figure 1. There is the normal gear reduction between the fast-rotating motor shaft and the entrance shaft to the filter. In addition, there are further reduction gears to a shaft, which does not move more than one revolution over the whole tuning path of the filter of -0.2 to $+0.2$ nm from the line center. Safety switches are placed around a wheel with switch notches on this slowest shaft. These switches prevent the filter from movement outside the tuning region by means of a simple relay system, which switches the motors directly, independently of the more complicate computer system for the control of the filter tuning in synchronization with the camera exposures, see Figures 1 and 2. Calibration of the zero point of this computer-controlled tuning system is realized with the help of two additional switches, one on the slow shaft with less than one revolution for the rough position and a second switch on the fast motor shaft for precise definition of the zero point.

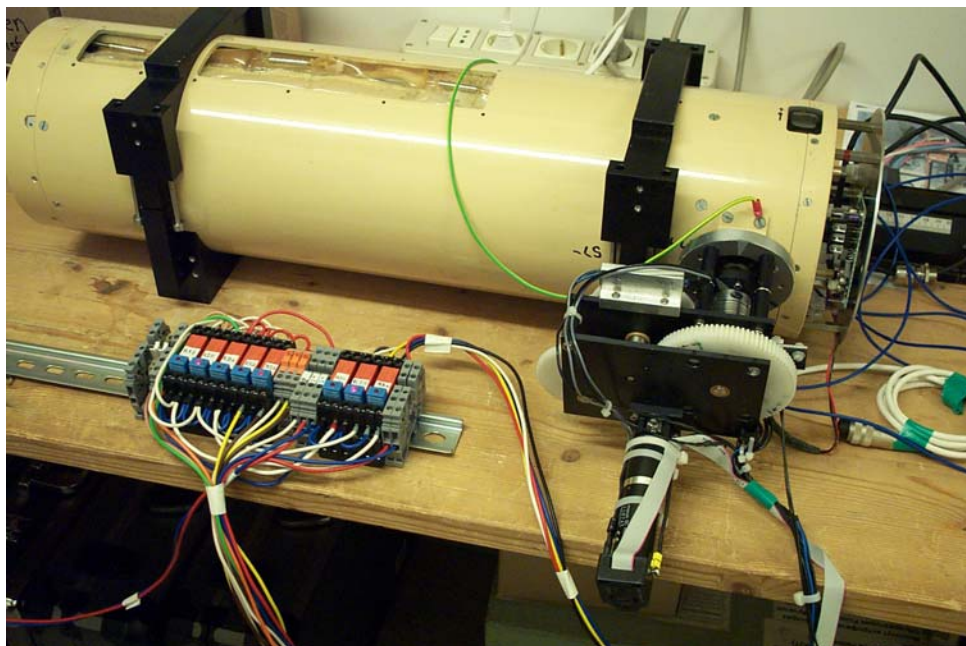


Figure 1. Barium filter in test set-up in the lab. The fast tuning system with servomotor is visible at the right bottom front. The large white gear wheel of PETP (Arnite) plastic is on the shaft to the filter and is driven by a small pinion on the shaft of the servomotor, the elongated black cylinder on the bottom front. The reduction gears to the shaft with less than one revolution over the whole tune region are at the left side of the large gear wheel. The safety and calibration switches are on the backside of the black gear plates. The relay-switches unit at the left bottom controls the safety switch and calibration system and also the information exchange with the computer system concerning the control of the filter tuning in synchronization with the camera exposures. The small elongated plastic bags visible in the elongated opening on top of the filter enable expansion of the oil in the filter with increasing temperature.

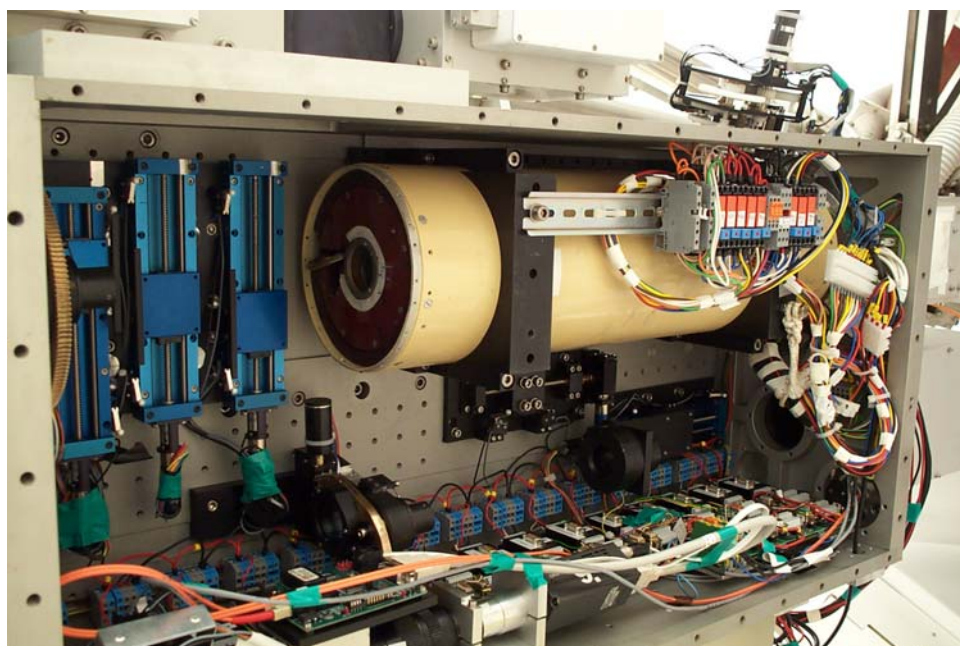


Figure 2. Assembly of Barium filter in telescope box. *Right top:* fast tuning system with underneath the relay-switches unit. *Bottom of box:* nearby-continuum channel with at left motor-driven filterwheel and at right the relay lens for imaging to the CCD camera. *Left:* slides for future polarizing elements in front of the Barium filter.

All optical elements of the Barium filter are in a tube filled with heavy oil, which possesses a high refractive index, close to the refractive index of the crystal plates and additional glass plates of the other optical components. This reduces the light loss by partial reflection at these plates. The Barium filter was newly filled with oil at Irkutsk shortly before the first successful test at the SVST. After the mentioned subsequent unsuccessful tests at the DOT and SST, it has been decided to open the Barium filter again at the lab at Irkutsk. It turned out that the oil inside the filter had become black, probably because of a chemical reaction between the oil and the metal surfaces of mousing and nickel in the filter. The used oil proved to be unsuitable for long-term use in the filter. This oil normally is used for shock-damping cylinders. Search was started for another oil, which resulted in the oil Dow Corning 705 Diffusion Pump Fluid. The refractive index of this oil is 1.58, close to the average refractive index of the crystal plates. This oil is designed for ultra-high vacuum applications. Its vapor pressure is extremely low and it has the highest phenyl content of all silicone diffusion pump fluids and, consequently, for the purpose here the highest index of refraction. The fluid for the optical application in the Barium filter was cleaned from all residual particles by filtering through special filters. After filling the filter with the cleaned oil, the fill opening was during several days coupled to a vacuum pump, while rotating the half-wave plates from time to time. In this way, all the remaining air in the oil was removed. Small elongated bags of plastic were connected to the oil-filled cylinder, see Figure 1. These bags easily expand under the oil pressure when the oil expands due to a temperature rise and the bags shrink again with a temperature drop. This avoids large pressure changes of the oil and, as a result, no oil leakage was experienced during operation, in contrast to the H α filter which is already for a longer time in operation at the DOT¹². Scientifically, the latter is exceptionally successful with its fast servo-tuning system for Doppler mapping. However, once or twice a season it has to be refilled with about 10 cc of oil because of oil leakage, mainly through the seal of the entrance shaft. Originally, also this filter was designed for hand-tuning. The combination of continual fast shaft rotation and the lack of an expansion bag causes the leakage.



Figure 3. Barium and H α filters at the Dutch Open Telescope. *Left bottom:* primary mirror. *Right top:* primary image. *Right bottom:* the H α -filter box close to the telescope structure, underneath the Barium -filter box and, hanging on it, a small box of the new temperature controller. Inside the smaller boxes at the lower left side are the CCD cameras with fiber links for, from left to right, Barium, H α , blue continuum near Ba and red continuum near H α .

Both the Barium and the H α filter are mounted on the DOT telescope structure, moving on an equatorial mount, see Figure 3. This setup has the advantage of no image rotation. However, the position of the filters relative to gravity, changes during the day. Despite this changing position, problems with air bubbles in the filters were never experienced. As mentioned, the H α filter has to be filled-up in time.

Moreover, a new temperature controller is developed for the Barium filter. It keeps the oil temperature in the filter within ± 0.02 °C of the required value of 38.36 °C during observations, also in the case that the temperature of the air around the open telescope changes rapidly several °C. The filter itself is provided with a thermal insulation layer on the outside and, in addition, the filter box on the telescope structure has an insulation layer on the inside wall surface. Consequently, the outside wall of the box is not heated by the filter and there is no negative effect on the seeing around the telescope.

The gear drives between the half-wave plates for tuning are situated inside the oil-filled cylinder. The drive shaft to the stage with the two 26.03 mm plates goes through an oil sealing. The shaft of the gear to the contrast stage with two 30.10 mm plates is connected through a coupling to the gear of the stage with the two 26.03 mm plates. The other side of the shaft of the 30.10 mm plates is a second shaft which goes outside the oil-filled cylinder through an oil sealing. This shaft end can be pulled out for decoupling and then, the contrast stage with 30.10 mm plates can be tuned separately, without opening the oil-filled cylinder. Normally, this separate tuning is not used. This second shaft towards the outside of the oil-filled cylinder drives a scale for the reading of the tuning position of the filter, which was used for the hand-tuning operation. Nowadays, the tuning position is determined by the computer system from the motor-shaft position with a 1000-counts-per-turn encoder in combination with the counting of the shaft revolutions. Zero-point calibration is done with two switches, one on the fast shaft and one on the slow less-than-one-revolution shaft, as described before.

Several improvements were made to the bearings of the drive system required for motor operation. In addition, a lock was made on the coupling to the contrast stage after it was experienced that decoupling occurred during fast motion by unexpected dynamical effects during fast rotation, as practised for the fast tuning with servomotor for the production of Doppler movies.

3. OBSERVATIONS WITH THE BARIUM FILTER

First results of observations with the Barium filter are shown in Figure 4. The Barium 4554 Å line is observed at 5 positions, relative to its line center: at - 80 mÅ, - 40 mÅ, 0 mÅ (line center), + 40 mÅ and + 80 mÅ. A Doppler-velocity image is produced from these five positions, see Figure 5. The nearby blue continuum is imaged as well underneath on the same scale for a comparison of where the velocities occur in the region of the spots themselves and around them.

In the velocity map of Figure 5, a positive velocity (= light color) corresponds to a red shift, matching with a downward motion towards the solar center, while a negative velocity (= dark color) corresponds to a blue shift, matching with an upward motion away from the sun. The downward motions in the granular lanes and the upward motions in the granular centers are clearly visible. High upward velocities next to downward motions are visible in the penumbra above the center of the large spot, somewhat to the left. Many small-sized high-velocity spikes, upward and downward, are visible in the umbra and transition region from umbra to penumbra of the large sunspot. A few of these spikes are visible in the small spots and pores at the left side of the image. The large spot's outside penumbra to the left bottom, the bottom and the whole right side shows a moderate downward flow with some small regions showing a high downward velocity.

Simultaneously taken images in H α are shown in Figure 6. This spectral line is also observed at 5 positions relative to the line center: at - 700 mÅ, - 350 mÅ, 0 mÅ (line center), + 350 mÅ and + 700 mÅ. The shifts relative to the line center are larger than for Barium, adapted to the broader line profile, the longer wavelength and the higher gas velocities in the higher solar atmospheric part, named the chromosphere, where the H α line is formed. Just like for Barium, a Doppler-velocity map is produced from these five positions, see Figure 7. And again, the nearby red continuum is imaged underneath on the same scale for comparison reasons. The longer wavelength of H α gives a lower diffraction-limited resolution for the 45-cm primary mirror. Consequently, a larger field can be imaged with an equal number of pixels without loss of resolution. In addition, the cameras of the H α and red continuum have a square field, hence, are different from the rectangular-field cameras used for the Barium and blue continuum.

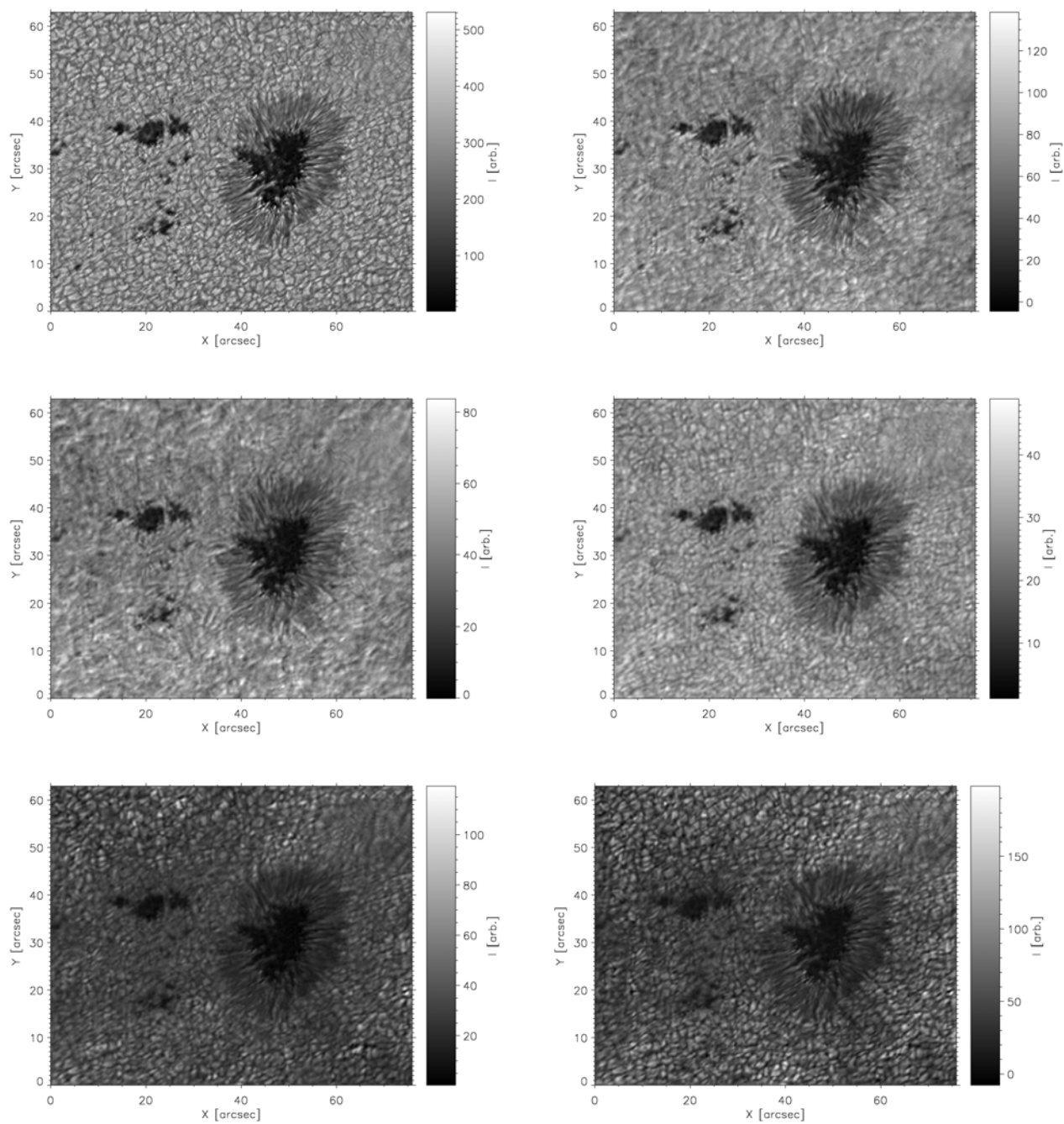


Figure 4. Barium images. *From left to right and top to bottom:* continuum, - 80 mÅ, - 40 mÅ, 0 mÅ (line center), + 40 mÅ, + 80 mÅ.

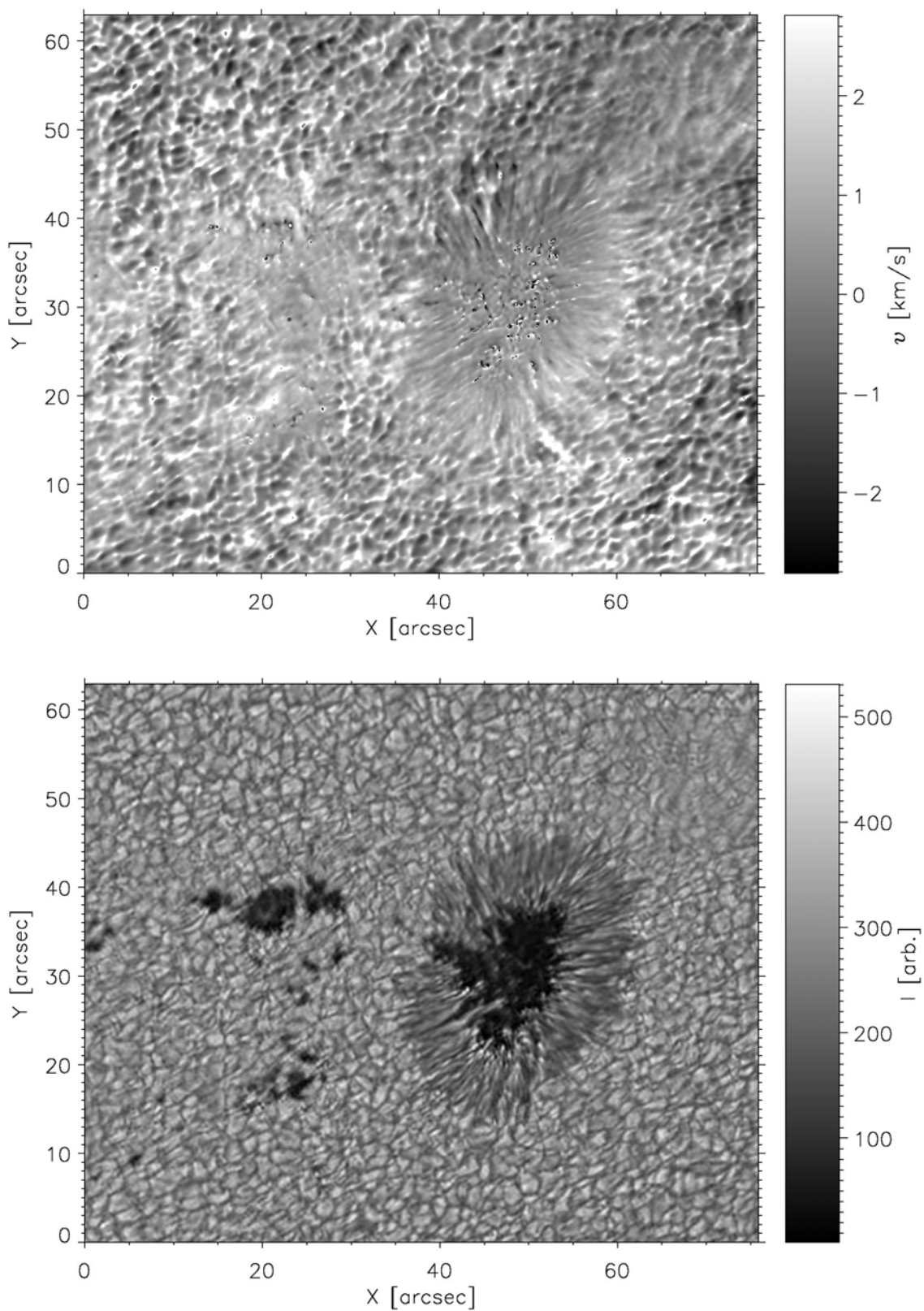


Figure 5. *Top:* Doppler-velocity map in Barium 4554Å. *Bottom:* simultaneous intensity map in nearby blue continuum 4505Å.

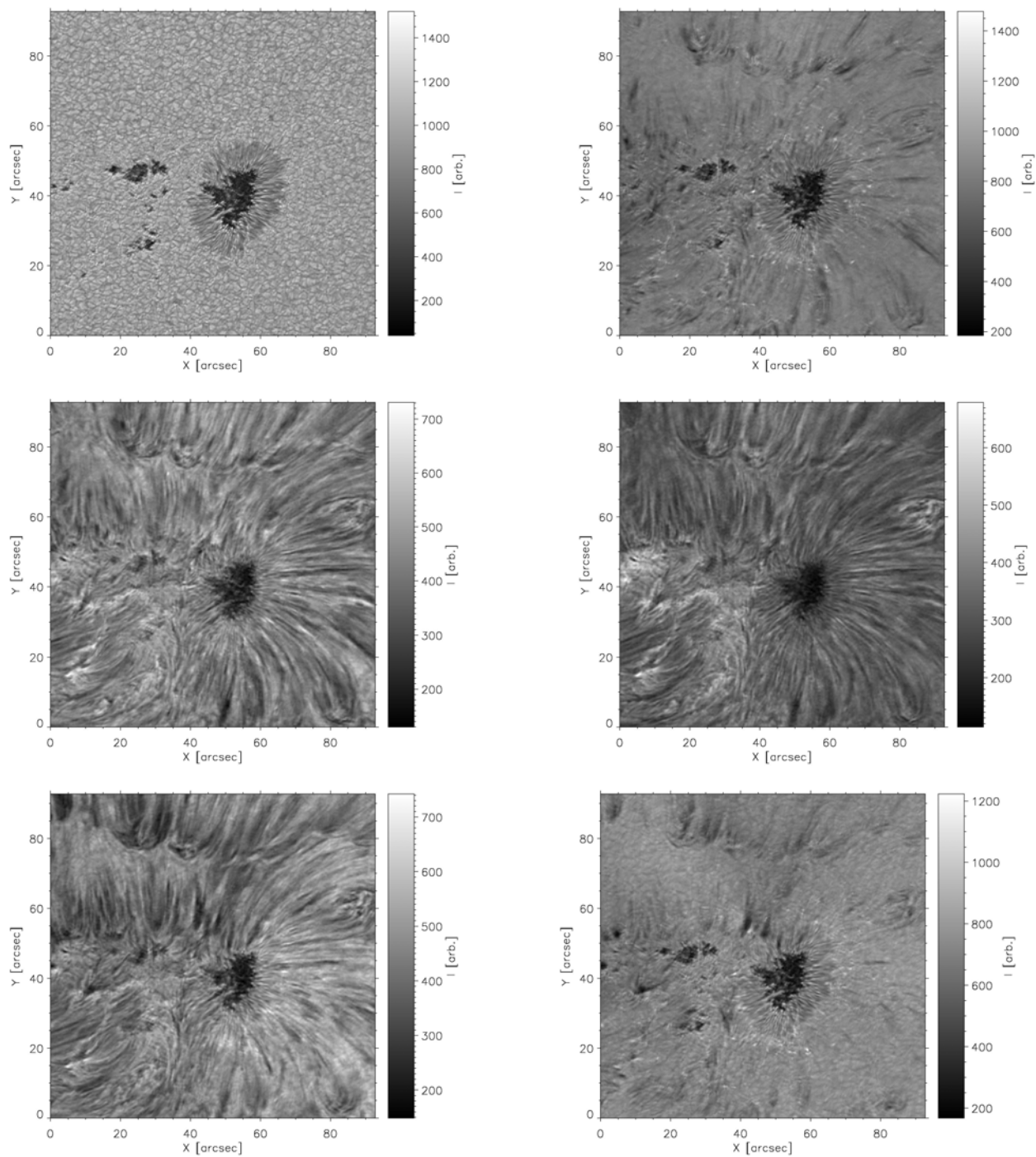


Figure 6. $H\alpha$ images. From left to right and top to bottom: continuum, $-700 \text{ m}\text{\AA}$, $-350 \text{ m}\text{\AA}$, $0 \text{ m}\text{\AA}$ (line center), $+350 \text{ m}\text{\AA}$, $+700 \text{ m}\text{\AA}$.

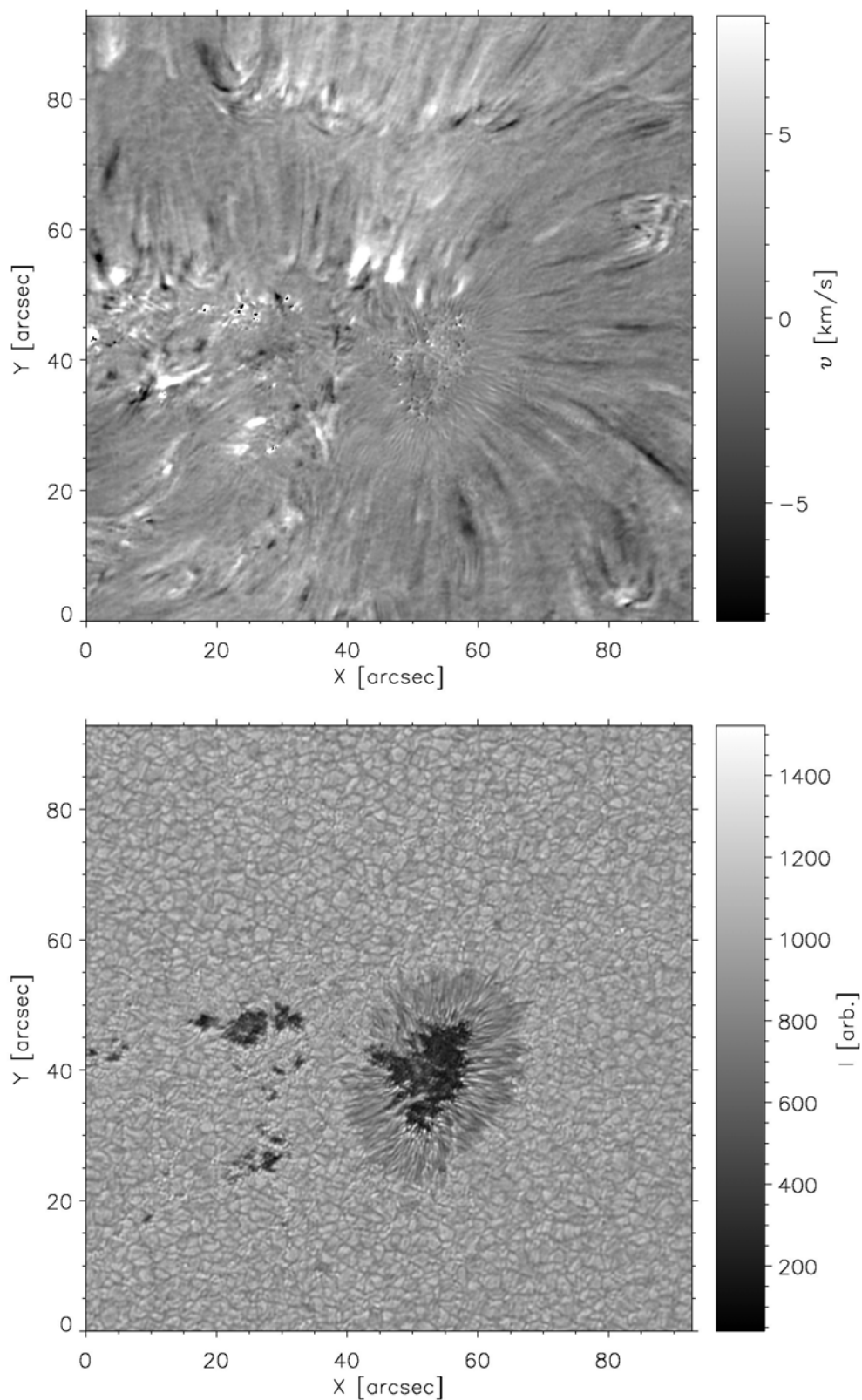


Figure 7. *Top:* Doppler-velocity map in H α 6563 Å. *Bottom:* simultaneous intensity map in nearby red continuum 6550 Å.

The H α Doppler-velocity map shows high velocities, upward and downward next to each other, in the same penumbra region as for Barium, at the top left side of the large spot. However, the elongated parts with same high velocity are larger in size and somewhat rotated to the right side, relative to the high-velocity streaks in the Barium Doppler image. The small-sized high-velocity spikes upward and downward occur in H α in the same regions as for Barium, in the umbra and transition region from umbra to penumbra. It is as if one is looking deeper into the solar atmosphere with H α in the spot center. However, the spikes in H α and Barium are not exactly at the same place and differ in pattern. Consequently, the H α and Barium patterns of spikes are not at the same height in the solar atmosphere. Further investigations will be useful. The high-velocity parts in and near the small spots and pores at the left side of the field are more pronounced in H α than in Barium.

4. CONCLUSIONS AND FUTURE PLANS

The Barium filter keeps a high light throughput with the new oil. The servomotor system and drives of the Barium filter now are working properly and allow the production of Doppler-velocity movies with the high spatial resolution of the DOT in the short-wavelength blue spectral region. To harvest the capabilities of this unique system, the KPF100 cameras used for the Barium and blue continuum have to be replaced by ES4020 cameras, as already in use for the H α and red continuum. The ES4020 cameras have a much lower noise level and a higher sensitivity. The replacement of the cameras for H α and red continuum reduced the exposure time from 12 msec to 5 msec, together with a strong reduction of noise. Comparison of the spectral sensitivity curves of the ES4020 and KPF100 cameras shows that the improvement for the blue spectral region will even be larger than for the red.

After replacement of the cameras, it will be of large scientific value to finish the full-stokes polarimeter for use in combination with the Barium filter. The mechanics for the polarimeter and for a calibration unit behind prime focus before the first inclined reflection are for the most part ready. The equatorial mount of the DOT has the advantage of no changing instrumental polarization and no pupil nor image rotation during the day.

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