Observing the solar corona with a tunable Fabry–Perot filter

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A solid Fabry–Perot etalon with a $0.16\text{ \AA}$ passband was used during the 180 s solar eclipse of 2006 for rapid scans of an emission line of the solar corona. The etalon was a *Y*-cut lithium niobate wafer coated with reflective and conductive (ITO) layers. Voltage applied perpendicular to the etalon face produced a passband shift of $0.0011\text{ \AA V}^{-1}$. During the eclipse, 18 filtergrams were obtained at six $0.22\text{ \AA}$ steps across the profile of the forbidden [Fe X] spectral emission line at $6374.4\text{ \AA}$, which results from the 10^6 K coronal plasma. The 9.3×9.3 arcmin field of view showed the structure of the corona above a newly emerged sunspot region. We discuss tests performed on the etalon before and after the eclipse. We also discuss the coronal observations, which show some features with 10 km s^{-1} velocities in the line of sight. © 2008 Optical Society of America

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1. Introduction

Total eclipses of the Sun present opportunities to study the distribution of emission in the solar corona, which is heated to $1 - 4 \times 10^6\text{ K}$ by mechanisms controversially explained by magnetohydrodynamic waves or nanoflares [1]. Most of the faint, forbidden emission lines in the visible spectrum of the corona come from highly ionized iron, and they must be studied with either a spectrograph or a narrow-bandpass filter. Because eclipses last only a few minutes, any filter must have a high throughput to enable exposure times of a few seconds despite the faintness of the corona ($\sim 10^{-5}$ relative to the solar disk) [2,3]. It is also important to be able to tune the filter through a spectral line—most are only about $1\text{ \AA}$ wide—to measure turbulent broadening

and Doppler shifts [4]. During the 29 March 2006 eclipse, we used a telescope with a 35 cm aperture and a tunable $0.16\text{ \AA}$ Fabry–Perot (F-P) etalon to study the emission from the forbidden [Fe X] line at $6374.4\text{ \AA}$. Observations were made from the Greek Island of Kastellorizo, just off the Turkish coast near the city of Kas. The duration of totality was only 3 min, and although the observations encountered some clouds, we obtained usable data on the structure of the corona above a newly emerged sunspot region [5–7]. We describe the optical system, especially the F-P filter and its wavelength calibration, our analysis of the coronal observations, and some tests of the etalon.

One of our objectives in undertaking the eclipse experiment was to test a solar filtergraph based on a lithium niobate (LiNbO_3) F-P etalon filter in a challenging environment. Subsequent to the eclipse, we performed a number of tests to qualify such a filter for operation in a space telescope.

2. Instrumentation

A. Telescope and Relay Optics

Figure 1 shows the optical system, and Table 1 lists the optical parameters. The telescope was a commercial 35 cm modified Ritchey–Chrétien design (Meade RCX400) fitted with a neutral density 5 “solar” filter for observations of the bright solar disk. The filter was removed at the beginning of the total eclipse to allow the full light-gathering power of the telescope to collect the weak coronal emissions. A telecentric optical system relayed the light from a 9.3×9.3 arcmin field of view (FOV) to the image plane of the camera.

The telecentric beam passed through an order-selecting multilayer thin-film filter. The FWHM passband of this filter (Andover Corporation) was $2 \text{ \AA}$, centered at $6374.5 \text{ \AA}$. Its peak transmission was 45%. It was surrounded by a temperature-controlled enclosure to keep the passband from drifting as the ambient temperature dropped during the eclipse. The lithium niobate F-P etalon was also in a temperature-controlled housing.

Focusing optics gave a plate scale of $68.4 \text{ arcsec mm}^{-1}$ at the detector, which was a 512×512 pixel cooled, frame-transfer CCD camera (Andor Ixon DV887) [8]. The plate scale was optimized to provide as large a FOV as possible consistent with a detector scale of about 1 arcsec mm^{-1} . Thus the image resolution was about 2 arcsec . One can hardly hope for higher resolution than that, considering that atmospheric turbulence during an eclipse degrades the wavefronts from the Sun. The exposure time of 6 s per frame was based on our calibrations in the field, consisting of pictures of the solar disk center through the density 5 filter (Thousand Oaks Optical).

B. Fabry–Perot Filter

The $0.16 \text{ \AA}$ filter was made by the Commonwealth Scientific and Industrial Research Organization’s Australian Centre for Precision Optics [9,10]. It is

Fig. 1. Schematic diagram of the 35 cm telescope, collimating optics, filters, and camera (focal) plane of the Williams College/Johns Hopkins University Applied Physics Laboratory eclipse filter-graph.

Table 1. Optical System Summary

Telescope aperture	35 cm
Effective focal length	301 cm
Plate scale	$68.4 \text{ arcsec mm}^{-1}$
Field of view	$9.3 \times 9.3 \text{ arcmin}$
Resolution	$1.1 \text{ arcsec pixel}^{-1}$
Pixel size	$16 \mu\text{m}$
Average spot size across field	$15.8 \mu\text{m}$
MTF at field center	0.443
Ray input angle at filter section (off axis)	1.14°

a polished wafer of Y-cut lithium niobate with a thickness of $199 \mu\text{m}$ and a surface flatness of about $\lambda/200$. The useful aperture is 60 mm, and peak transmission is $\sim 70\%$. The faces are coated with reflective and conducting films. The reflective coatings combine with the extreme flatness to give the filter a finesse of about 27. This means that the width of the passbands is about 0.037 times the free spectral range, which is $4.3 \text{ \AA}$. As seen in Fig. 2, our measurements confirmed that the passbands are separated by $4.3 \text{ \AA}$. The figure is based on data taken with a laboratory spectrometer of only $1 \text{ \AA}$ resolution, so the $0.16 \text{ \AA}$ passbands are widened, but the widening had little effect on the objective of the laboratory tests, which was to establish the passband peak positions as a function of voltage and temperature. There are actually two sets of passbands, one for the e-ray and one for the o-ray. In our case a linear polarizer blocked the e-ray light transmitted by the filter. The electro-optic sensitivity of the e-ray in the Y-cut etalon is much less than for the o-ray [11].

The conductive coatings are in contact with electrodes that can apply up to 2500 VDC in either direction perpendicular to the etalon faces. As described in Refs. [11,12], voltage applied to a Y-cut LiNbO_3 crystalline wafer changes the refractive indices and thickness. In the etalon used at the eclipse, voltage produced a shift of the o-ray passbands of $0.0011 \text{ \AA V}^{-1}$. The large voltage sensitivity allowed us to scan the passband from the peak of coronal

Fig. 2. (Color online) Diode laser line spectrum (gray curve) and the transmission spectrum (black curve) of the Fabry–Perot etalon showing three passbands. The true F-P profiles are much narrower than shown here, because they were broadened in the spectrograph. True laser linewidth = 1 ; true F-P passband = $0.16 \text{ \AA}$.

forbidden Fe X line at $6374.4\text{ \AA}$ into the nearby continuum, which can be subtracted from the on-band observations to produce high-purity images of the $6374.4\text{ \AA}$ line. All the images shown in this paper have had the continuum contribution subtracted out.

Figure 2 shows the etalon filter's passbands relative to a thermoelectrically cooled diode laser (World Star) tuned to $6375.16\text{ \AA}$. The power output stability of the laser module is better than 1%, so it provides a good reference to check the etalon's passband position in the field and in the laboratory. In the days and hours before the eclipse, we pointed the telescope at the laser and adjusted the temperature and voltage on the etalon until we could be sure of tuning to the coronal line, which is $0.76\text{ \AA}$ from the laser wavelength. It was a great advantage to have this capability at the eclipse site, because the temperature sensitivity of the passbands in the Y-cut etalon is quite high, $0.19\text{ \AA }^{\circ}\text{C}^{-1}$, and we could not be sure that the actual temperature of the etalon was equal to the indicated filter housing temperature. We estimate that any change in filter temperature during the 3 min of observations was $<0.05\text{ }^{\circ}\text{C}$, which translates to a wavelength uncertainty of $<0.01\text{ \AA}$.

During the eclipse, we could tune the LiNbO_3 filter over only a 1000 V range because of the failure on the site of the primary 2500 V power supply. As shown in the next section, however, this voltage range was enough to sweep from the line center at $6374.4\text{ \AA}$ to the nearby continuum at $6375.5\text{ \AA}$. Exposures were made at 200 V steps from 1000 to 0 V at a cadence of 10 s per step. We obtained the most useful data during the first series of exposures, which were not degraded by clouds. Eighteen exposures were obtained during the 180 s duration of totality.

3. Results

A. Fe X Emission in Active Region 10866

Although the Sun had been relatively inactive in the days and weeks before the eclipse, it developed a new sunspot region on 29 March. Called Active Region NOAA 10866, it was on the east limb at $S6^{\circ}$ when the eclipse began at Kastellorizo. Figure 3 shows how most of the Sun appeared in the extreme ultraviolet (EUV) emission of Fe X at $171\text{ \AA}$, as recorded from space by the EUV Imaging Telescope (EIT) on the Solar and Heliospheric Observatory. The insets show one of our images in the Fe X visible emission and an EIT image of the Fe XIV $195\text{ \AA}$ emission. In Fe X the active region is very different from its appearance in the Fe XIV line, which originates in plasma at $4 \times 10^6\text{ K}$. The Fe X emitting plasma is at a temperature of about $1.5 \times 10^6\text{ K}$. There is only fair agreement between our Fe X visible (red) image and the EUV image at $171\text{ \AA}$. It is not surprising that the two images should differ somewhat, because the filter used to isolate the $171\text{ \AA}$ Fe X emission is broad enough to include some emission from cooler Fe IX ions [13].

Fig. 3. (Color online) Visible (red) light and EUV coronal features compared. Active Region NOAA 10866 was on the east limb at $S06$ at the beginning of totality at 1050 UT on 29 March 2006. The middle inset image of light from Fe X shows the structure of the active region as seen from the ground during the eclipse. The blue (left) and green (right) images are EUV observations of Fe X and Fe XIV from the EIT/SOHO telescope in space.

Poor seeing, from atmospheric turbulence, and telescope tracking errors, resulting from a brief power outage a few hours before the eclipse that zeroed our previously stored guiding model, blurred the images somewhat, but as Fig. 4 shows, deconvolution can bring out interesting structure on an ~ 10 arcsec scale. We deconvolved the images by first flat-fielding them, i.e., subtracting from the individual raw images corresponding images of the preeclipse

Fig. 4. Left: image showing structure of the corona above the sunspot region before deconvolution. Right: this image has been deconvolved, and it shows radial structures and low-lying coronal loops. Poor seeing and telescope tracking errors smeared the original images, but deconvolution restores much of the detail of the coronal active region features.

sky taken of each of the six discrete F-P voltage settings used during the observations. Point spread functions (PSFs) from four regions of interest were then generated from the system optical model. The regions correspond to a rectangular subset of pixels along the solar limb and upper and lower centers of the full raw image. The flat-fielded images were then iteratively deconvolved with the four PSFs and normalized.

To correct for tracking errors, the solar center in pixel space of each image was found through limb identification and knowledge of the image plate scale. Then, fourth-order polynomials were fitted to the horizontal and vertical motions of the sequence of images. The appropriate shifts were then applied to remove the apparent motion of the PSF deconvolved images. A small correction in image rotation was also made based on apparent motion of the observed active region and computed image rotation during the 3 min of the observations. The final co-registered, deconvolved images were then stacked for convenient viewing. The registration error is on the order of ± 4 pixels.

B. Spectral Line Variations

There are many reports of motions in the corona [14,15] ranging from $< 10 \text{ km s}^{-1}$ up to $\sim 100 \text{ km s}^{-1}$. Figure 5 is our velocitygram of the coronal features above the sunspot region. The right-hand side of the figure shows a subtraction of the image with the filter tuned at $400 \text{ V} = \Delta\lambda \approx -0.44 \text{ \AA}$ relative to line center from the image with the filter tuned to the center of the line. The variations in brightness reveal several interesting features moving in the line of sight. In this Doppler image, the coronal plasma in the dark parts was moving toward the observer.

To have a closer look at the spectral line profiles in the various features, we sampled the mean intensity

Fig. 5. The grayscale in the right-side image represents Doppler shifts that result from solar plasma motions along the line of sight. This velocitygram reveals several places in the coronal structures where the hot plasma has a velocity component of $\sim 10 \text{ km s}^{-1}$ toward the observer. The image on the left shows the locations of the areas sampled to produce the line profiles shown in Fig. 6.

in the boxes shown and plotted the results as a function of filter-offset voltage. The results are shown in Fig. 6. Most of the line profiles have a half-width at half-maximum of about $400 \text{ V} = 0.44 \text{ \AA}$, so the full width is nearly an angstrom. However, the mean profiles in boxes 7 and 8 are shifted to shorter wavelengths by about $0.2 \text{ \AA}$. Assuming that these profiles are Doppler shifted and the others are not, our results imply a near zero line-of-sight velocity in most features and only 10 km s^{-1} toward the observer in the coronal features labeled 7 and 8. In other words, we do not detect velocities $> 10 \text{ km s}^{-1}$, as found by some observers [16].

We conclude that the $0.16 \text{ \AA}$ LiNbO₃ filter is a useful tool for rapidly obtaining coronal spectral-line profiles during the short-lived opportunities offered by solar eclipses. The filter operated well under the difficult field conditions that prevailed in Kastellorizo, and can be expected on any eclipse expedition. Eclipse expeditions are like space missions in some ways, which is why we took the LiNbO₃ filter to Kastellorizo. However, space missions present different unique challenges, so we performed some laboratory tests on the filter that are appropriate to qualify it for use in space.

4. Tests for Energetic Proton or γ Ray Damage

Subsequent to the eclipse, we tested the capability of two LiNbO₃ wafers similar to the one used for eclipse observations to withstand conditions frequently encountered in space. One hazard is bombardment by solar flare-produced high-energy ions. We bombarded the etalons with a high-energy proton beam. One wafer was subjected to a fluence of 10 krad and the other to 20 krad. To gauge the effect, we measured the second wafer's spectral transmission for all wavelengths between 4500 and 11500 $\text{\AA}$ before and after the 20 krad exposure. There was no detectable change ($< 1\%$) in light transmission through the wafer at any wavelength. We conclude that a LiNbO₃

Fig. 6. Normalized profiles of the Fe X 6374 $\text{\AA}$ line in the boxed areas shown in Fig. 5. The numbers in the plot area refer to the 8 boxes in Fig. 5. The profiles in boxes 7 and 8 are blueshifted by about $0.22 \text{ \AA}$ relative to the others. The conversion factor from voltage applied to the F-P filter to wavelength change is $1 \text{ \AA}/900 \text{ V}$.

filter will not be damaged even in a solar flare-produced proton shower.

To test for changes in the index of refraction of a LiNbO_3 filter subjected to gamma radiation, we opted to use a working F-P etalon with optical-quality surfaces. This etalon was previously used in the Flare Genesis Solar Vector Magnetograph that was flown over Antarctica in January 2000 in a balloon gondola [17]. The flight achieved its objective to measure Doppler shifts and Zeeman shifts in growing sunspot regions.

While there is usually no radiation hazard on a stratospheric balloon flight, the radiation hazard on space missions is significant. Any changes in the F-P filter's index of refraction, i.e., optical damage resulting from exposure to radiation, will also change the optical path within the F-P etalon and thus change the wavelengths of the passbands. For our laboratory tests of the etalon, we tuned one passband to near the wavelength of a He-Ne laser and beamed the laser through the etalon. Tuning was accomplished by varying the high voltage just as during the eclipse observations. A photodetector behind the etalon measured the transmitted laser beam intensity. Any change in the F-P etalon index of refraction due to the gamma radiation would shift its passband and change the transmission of the laser light.

We recorded the transmission versus voltage before and after exposure to high-energy γ radiation for total doses of 10 and 20 krad. After each dose, the high-voltage scans were repeated, always at the same temperature. The resulting before and after transmission profiles are plotted in Fig. 7. The peaks of transmission at both 10 and 20 krad are almost exactly coincident with the baseline peak. The large change in peak transmission for the two scans at 20 krad likely results from a change in the oven temperature of about 0.2°C between the beginning of the first scan and the end of the second scan. We conclude that exposure to 20 krad of gamma radiation does not change the index of refraction of the tested etalon.

Fig. 7. High-voltage scans for F-P etalon #75-1 at gamma ray doses of 10 and 20 krad and a baseline scan performed at 0 krad.

5. Conclusions

The tunable lithium niobate F-P etalon is a convenient, high-throughput, and rugged tool for imaging solar coronal lines and measuring the Doppler shifts that result from line-of-sight velocities. We found localized velocities of -10 km s^{-1} above active region NOAA 10866 at the instant of the solar eclipse of 29 March 2006. Kim [18] also reported seeing large-scale features with velocities of 10 km s^{-1} during the eclipses of 1972 and 1981. In 95% of the line profiles she measured, the velocities were less than 20 km s^{-1} . We did not find higher velocities, such as those reported by some others [16], including one of us, from photographic F-P observations. However, we sampled only one active region for one instant, so our results are not inconsistent with reports of higher velocities [19]. We note that, during the 2006 eclipse, Pasachoff *et al.* [20] found a coronal plume that showed motion at 65 km s^{-1} .

We found that the loops and other features in the Fe X 6374 Å images of $1.5 \times 10^6\text{ K}$ plasma obtained from the ground differ in detail from loops recorded in Fe IX—X 171 Å and Fe XIV 195 Å from space. The reason for the differences in the two Fe X images is the contamination of Fe X by Fe IX emission. The coronal structures in Fe XIV, which is formed at $4 \times 10^6\text{ K}$, should differ even more because active regions are definitely not isothermal.

We conclude that the 0.16 Å LiNbO_3 filter is a useful tool for rapidly obtaining coronal spectral line profiles under the short-lived opportunities offered by total solar eclipses. Our preliminary results indicate that data from future eclipse observations will yield useful velocity and active region structure information that may be relevant to the difficult problem of solving how the corona is heated.

The high energy proton and gamma radiation tests that we performed demonstrate that a solid state LiNbO_3 F-P etalon can withstand radiation environments up to 20 krad and proton energies of 100 MeV without changes in performance. We also tested the LiNbO_3 wafers in a vibration environment that simulates vibration during a launch into space. There was no damage, so we conclude that LiNbO_3 narrow-band F-P filters can be successfully flown in space. These filters could be the main component of a compact solar vector magnetograph on a deep space mission such as the Solar Orbiter.

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References

1. J. A. Klimchuk, "On solving the coronal heating problem," *Sol. Phys.* **234**, 41–77 (2006).
2. L. Golub and J. M. Pasachoff, *Nearest Star: the Surprising Science of Our Sun* (Harvard University, 2001), p. 267.
3. T. Chandrasekhar, N. M. Ashok, J. N. Desai, J. M. Pasachoff, and K. R. Sivaraman, "Fabry–Perot interferometric observations of the coronal red and green lines during the 1983 Indonesian eclipse," *Appl. Opt.* **23**, 508–511 (1984).
4. T. Chandrasekhar, N. M. Ashok, B. G. A. Rao, J. M. Pasachoff, and T.-A. Suer, "Fabry–Perot interferometric study of the green coronal line during the total eclipse of 2001 from Zambia," presented at the 26th Meeting of the IAU, Solar Active Regions and 3D Magnetic Structure, Prague, Czech Republic, 16–17 August 2006, paper JD03 #2.
5. J. M. Pasachoff and M. A. Bruck, "High-spectral-resolution observations of the solar chromosphere and corona," *Bull. Am. Astron. Soc.* **39**, 224 (2007).
6. D. M. Rust, M. W. Noble, J. M. Pasachoff, B. A. Babcock, M. A. Bruck, and R. A. Wittenmyer, "Narrow-band filter observations of the red-line corona at the 29 March 2006 eclipse," *Bull. Am. Astron. Soc.* **38**, 217 (2006).
7. J. M. Pasachoff, B. A. Babcock, S. P. Souza, M. A. Bruck, P. W. Hess, S. B. Kimmel, J. S. Levitt, A. S. Steele, A. E. Tsykalova, D. M. Rust, M. W. Noble, R. Wittenmyer, J. H. R. L. Kern, J. H. Seiradakis, A. Voulgaris, G. Pistikoudis, J. Nestoras, and M. Demianski, "Coronal observations at the 29 March 2006 total solar eclipse," *Bull. Am. Astron. Soc.* **37**, 216 (2006).
8. S. P. Souza, B. A. Babcock, J. M. Pasachoff, A. A. S. Gulbis, J. L. Elliot, M. J. Person, and J. W. Gangestad, "POETS: Portable Occultation, Eclipse, and Transit System," *Publ. Astron. Soc. Pac.* **118**, 1550–1557 (2006).
9. C. H. Burton, A. J. Leistner, and D. M. Rust, "Electrooptic Fabry–Perot filter: development for the study of solar oscillations," *Appl. Opt.* **26**, 2637–2642 (1987).
10. R. P. Netterfield, C. H. Freund, J. A. Seckold, and C. J. Walsh, "Design of a lithium niobate Fabry–Perot etalon-based spectrometer," *Appl. Opt.* **36**, 4556–4561 (1997).
11. D. Bonaccini and R. N. Smartt, "Lithium niobate double channel Fabry–Perot interferometer for solar corona uses," *Appl. Opt.* **27**, 5095–5102 (1988).
12. D. M. Rust, "Etalon filters," *Opt. Eng.* **33**, 3342–3348 (1994).
13. J. P. Delaboudiniere, G. E. Artzner, J. Brunaud, A. H. Gabriel, J. F. Hochedez, F. Millier, X. Y. Song, B. Au, K. P. Dere, R. A. Howard, R. Kreplin, D. J. Michels, J. D. Moses, J. M. Defise, C. Jamar, P. Rochus, J. P. Chauvineau, J. P. Marioge, R. C. Catura, J. R. Lemen, L. Shing, R. A. Stern, J. B. Gurman, W. M. Neupert, A. Maucherat, F. Clette, P. Cugnon, and E. L. Van Dessel, "EIT: Extreme-Ultraviolet Imaging Telescope for the SOHO Mission," *Sol. Phys.* **162**, 291–312 (1995).
14. A. B. Delone and E. A. Makarova, "Interferometric investigation of the red and green coronal lines during the total solar eclipse of May 30, 1965," *Sol. Phys.* **9**, 116–130 (1969).
15. D. H. Liebenberg, R. J. Bessey, and B. Watson, "Observed coronal temperatures at 1.37 solar radii in the region of a helmet structure," *Sol. Phys.* **40**, 387–396 (1975).
16. T. Chandrasekhar, J. N. Desai, N. M. Ashok, and J. M. Pasachoff, "Fabry–Perot line profiles in the 5303 Å and 6374 Å coronal lines obtained during the 1983 Indonesian eclipse," *Sol. Phys.* **131**, 25–39 (1991).
17. P. Bernasconi, D. M. Rust, and H. A. C. Eaton, "High resolution vector magnetograms with the Flare Genesis vector polarimeter," in *Advanced Solar Polarimetry—Theory, Observation, and Instrumentation*, Astron. Soc. Pac. Conf. Ser. 236, 399–406 (2001).
18. I. S. Kim, "On the Fabry–Perot investigations of the solar corona: eclipse observations of large-scale dynamics," *Adv. Space Res.* **14**, 45–48 (1994).
19. I. S. Kim, "Eclipse spectra of the coronal velocity field (invited review)," in *Last Total Solar Eclipse of the Millennium in Turkey*, Astron. Soc. Pac. Conf. Ser. 205, 69–82 (2000).
20. J. M. Pasachoff, V. Rusin, M. Druckmüller, H. Druckmüllero-vá, M. Bělík, M. Saniga, M. Minarovjech, E. Markova, B. A. Babcock, S. P. Souza, and J. S. Levitt, "Polar plume brightening during the 29 March 2006 total eclipse," *Astrophys. J.* **682**, 638–643 (2008).