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SUNSPOT OBSERVATIONS FROM THE SOUP INSTRUMENT ON SPACELAB 2

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ABSTRACT

A series of white light images obtained by the SOUP instrument on Spacelab 2 of active region 4682 on August 5, 1985 have been analyzed in the area containing the sunspot. Although the umbra of the spot is underexposed, the film is well exposed in the penumbral regions. These data have been digitially processed to remove noise and to separate p-mode oscillations from low velocity material motions. The results of this preliminary investigation include: (1) proper motion measurements of a radial outflow in the photospheric granulation pattern just outside the penumbra; (2) discovery of occassional bright structures ("streakers") that appear to be ejected outward from the penumbra; (3) broad dark "clouds" moving outward in the penumbra in addition to the well known bright penumbral grains moving inward; (4) apparent extensions and contractions of penumbral filaments over the photosphere; and (5) observation of a faint bubble or loop-like structure which seems to expand from two bright penumbral filaments into the photosphere.

1. Introduction

Although the Spacelab 2 mission was flown during the sunspot minimum of the solar cycle, we were fortunate enough to have a medium size sunspot and a group of pores on the disk during the week of the mission. The high resolution (approximately 0.5″ or 350 km) and, more importantly, the stability and freedom from variable atmospheric distortion of the SOUP data has provided an unprecedented opportunity to study the dynamics of a sunspot in "white light" by viewing and analyzing movie sequences. Unfortunately, the umbra was underexposed and there we can only set upper limits on the brightness of any structures but the penumbra and the surrounding photosphere show a large variety of interesting phenomena. Many of these have not been previously described. Figure 1 is a cartoon which summarizes and indicates the locations of some of these phenomena.

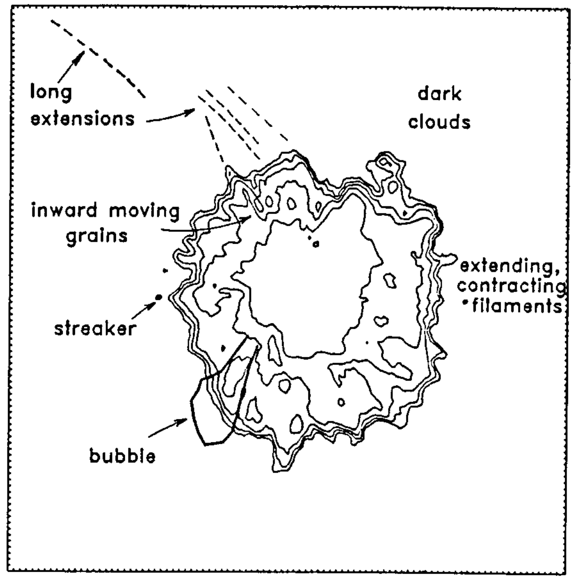

Fig. 1 A cartoon indicating locations of various phenomena. The ticks marks are spaced every arc second.

2. Observations

A description of the SOUP instrument and a summary of the data obtained are given by Title *et al.* (1986). White light film images containing the sunspot in the field of view were obtained during portions of 5 orbits. The longest uninterupted sequence was exposed during Rev 110 and consists of about 28 minutes of data with a frame taken every 2 seconds on August 5, 1985 between 19:10 – 19:38 GMT. Analysis of the guider data indicates that the image was stable with an RMS jitter of about 3 milli arc seconds. All of the analysis reported in this paper has used this particular sequence. We have digitized every fifth frame over the entire interval to give us data with 10 second spacing. Processing every frame will allow us to further reduce the noise and improve the quality of the images in the future.

Our analysis has benefited greatly from use of an interactive video viewing system and from a number of image processing techniques including 3-D fourier filtering. A optical video disk recorder/player allows recording large numbers of computer-generated images which can then be played back interactively as movie loops or single frames. Although most of the phenomena described in this paper can be recognized in the raw digitized data (when one knows what to look for), some may have never been discovered without viewing processed movies. The fourier filtering has allowed us to suppress the effects of the suprisingly strong p-mode oscillations, remove noise in the data, and enhance or suppress motions within any desired velocity range. The work described here and in the preceeding paper (Title, *et al.* 1987) seems to be the first major application of these techniques for processing movies of solar data. They are very useful tools and we expect to see them used extensively in the future in spite of the demands they make on computer time and storage.

Figure 2 shows a series of 12 images spaced two minutes apart which were taken from a sequence

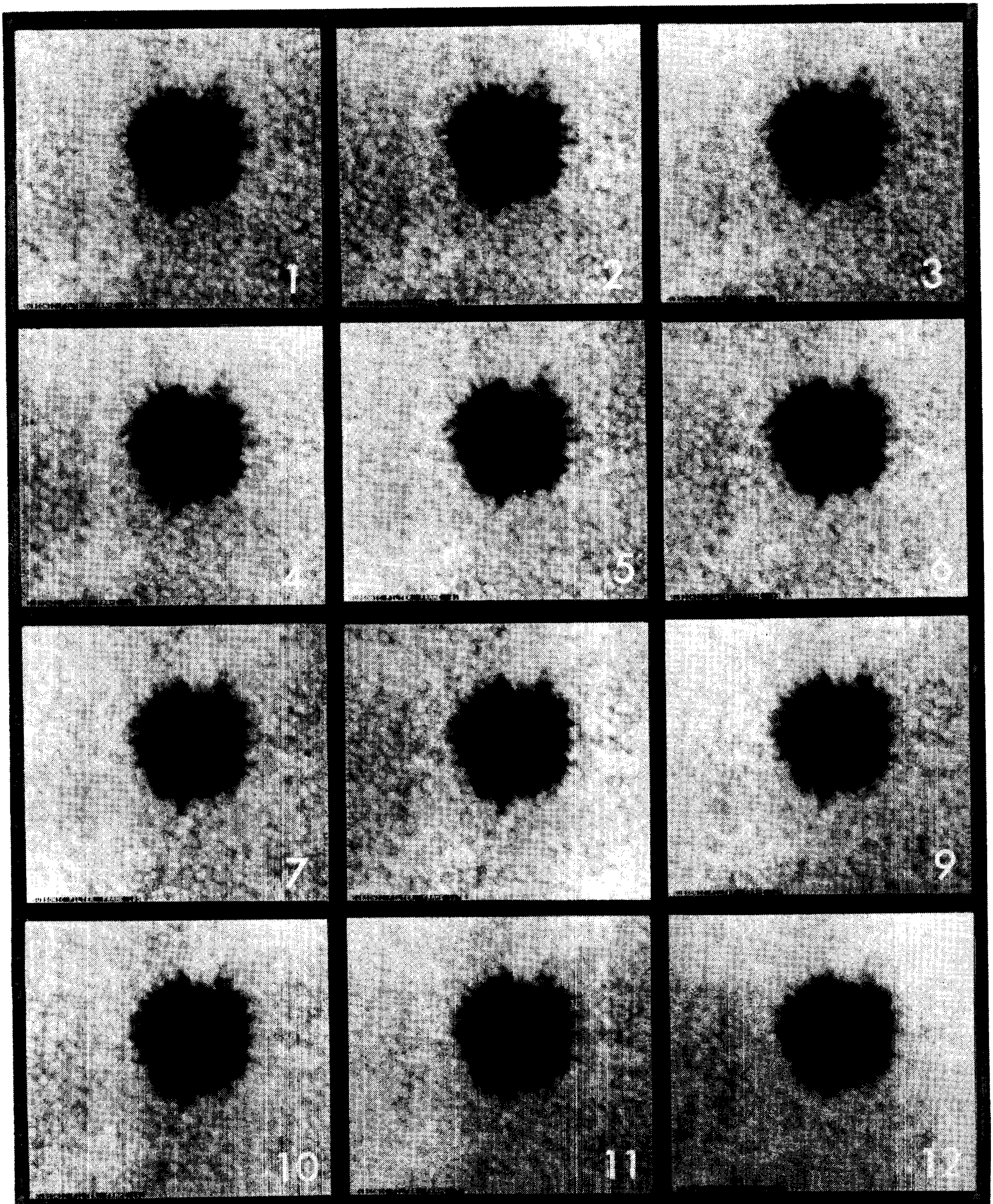

Fig. 2 Twelve images of the sunpot spaced two minutes apart. This is subsonic filtered data with a velocity cutoff of 4 km/s.

processed with a "subsonic" fourier filter. This was done by zeroing all fourier components in (k_x, k_y, ω) space with phase velocities greater than 4 km/s. This is very effective at removing noise and suppressing the p-mode oscillations (Title, *et al.* 1987).

3. Results

3.1 Granulation Outflow

The area immediately surrounding the sunspot penumbra shows a radial outflow that is clearly visible even in the unprocessed movies, especially when run at high speed (60 frames/s which is 600 times real time). The apparent width of this "collar flow" is $\approx 5''$. Movies temporally filtered to suppress the p-mode oscillations show the motion more clearly and allow an estimate of the velocities of individual granules. These range from 0.2 to 1.5 km/s. The radial time slices through the sunspot shown in figure 3 are the most convincing displays of radial flows. The radially advecting granules appear in these images as slanted lines. The radial velocity can be determined from the slope.

This advection of the granules is also clearly seen in the flow maps generated by local correlation tracking as shown in figure 4. The maps represent the transverse flow averaged over the entire 28 minute span available. The technique used to make this flow map is described by November, *et al.* (1987).

These proper motions have apparently not been previously reported although their doppler signature would explain observations of outflows beyond the penumbra in studies by Kinman (1952) and Sheeley and Bhatnagar (1971). Because the flow around the penumbra had lower velocities and because of pattern similarities in their dopplergrams, Sheeley and Bhatnagar suggested that the flows were more closely related to the pattern of supergranulation than the penumbral Evershed effect. This is consistent with the SOUP observations.

The relationship of these motions to the photospheric Evershed effect is unclear although both represent radially outward flows. The moving granules could be upward convention deflected by the slanted magnetic field under the photosphere or part of a large scale convection pattern around the sunspot. It is generally accepted that the Evershed effect is concentrated in dark penumbral lanes (based on observations of Beckers (1968) and Abdusamatov and Krat (1970)) and that the velocities end abruptly at the penumbral boundary (e.g., Wiehr, *et al.*, 1986). These dark penumbral filaments may be elevated relative to the surrounding photosphere (e.g., Moore, 1981). Actually, this granulation advection is probably the source of confusion over whether the Evershed effect actually ends abruptly at the penumbra. The granular motion may or may not show up in an individual spectra but it would clearly be present in any adequate average or under conditions of poor seeing.

3.2 Fast Ejections ("Streakers")

Around the penumbra there are bright granule-like features that seem to be ejected from the sunspot. The most obvious of these bright features, dubbed the "streaker", travels at about

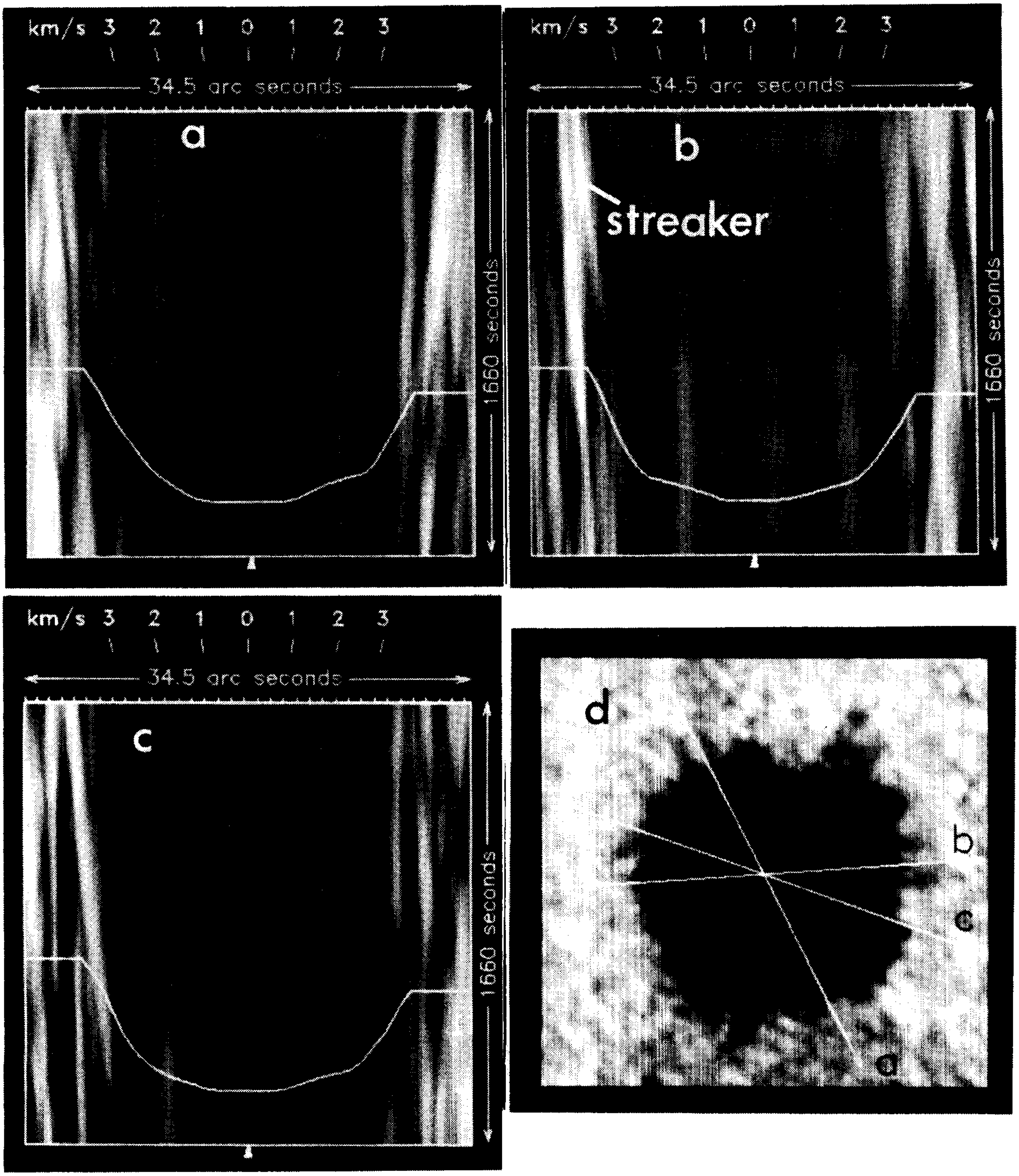

Fig. 3 Parts a, b, and c are space-time slices through the sunspot with the spatial sections indicated in part d which is an image at the center of the time range. These are called radial slices because the spatial sections are along a line passing through the center of the spot.

2.7 km/s. The normal granulation outflow is at $\frac{1}{3}$ to $\frac{1}{2}$ that rate. Thus, the bright moving features move through (perhaps as a wave) or over the granulation.

The radial trajectory of the streaker is clearly shown in figure 3b, one of the time slices through the sunspot. A dark structure appears to originate in conjuction with the streaker and moves in

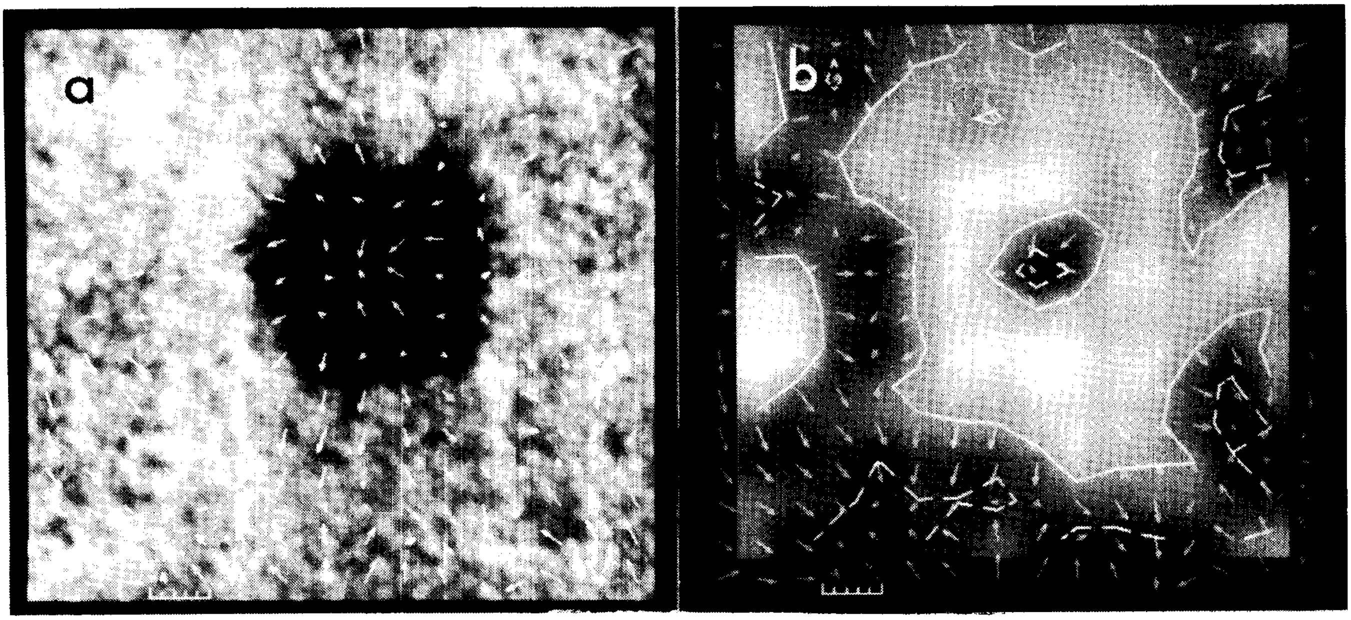

Fig. 4 (a) A map of horizontal flows indicated by the arrows and (b) an image of the computed horizontal divergence of this flow. Bright areas have positive divergence (outflowing material, probably upwelling) and dark areas have negative divergence (inflowing material).

the opposite direction into the penumbra. The streaker approaches another bright photospheric structure which is also moving outward from the spot at 0.95 km/s. Another streaker is seen in figure 3c.

We have not yet made a thorough study of these bright structures. However, they are clearly related to activity of the nearby penumbra. Further understanding will require measurements of the interaction of the penumbral filaments with the photosphere surrounding the sunspot.

3.3 Ejected Loop or Bubble

A very interesting feature was discovered by examining movies of images such as the one in figure 5. This is one frame in a movie which has velocities in the range 2 - 4 km/s enhanced by 3-D fourier filtering. This was accomplished by multiplying the appropiate fourier coefficients by 2. A large loop or bubble is seen which seems to be associated with two bright penumbral filaments. It begins in the penumbra and travels out into the surrounding photosphere. Although much easier to see in figure 5, the same structure can be seen in the corresponding frame in figure 2 (image # 11 which is frame 153 in the movie) and in the raw images. We have no information on the height of this structure in the atmosphere but it may be easier to understand energetically if it represents an ejected mass above the photosphere.

3.4 Penumbral Filaments

Dynamics: It is evident from the movies, and images separated in time by more than five or ten minutes, that some penumbral filaments or groups of filaments extend and contract at rates of 0.1 to 0.5″/minute (1.2 to 6 km/s). These might be actual motions of filaments or possibly waves propagating through the filaments which cause temperature or density changes

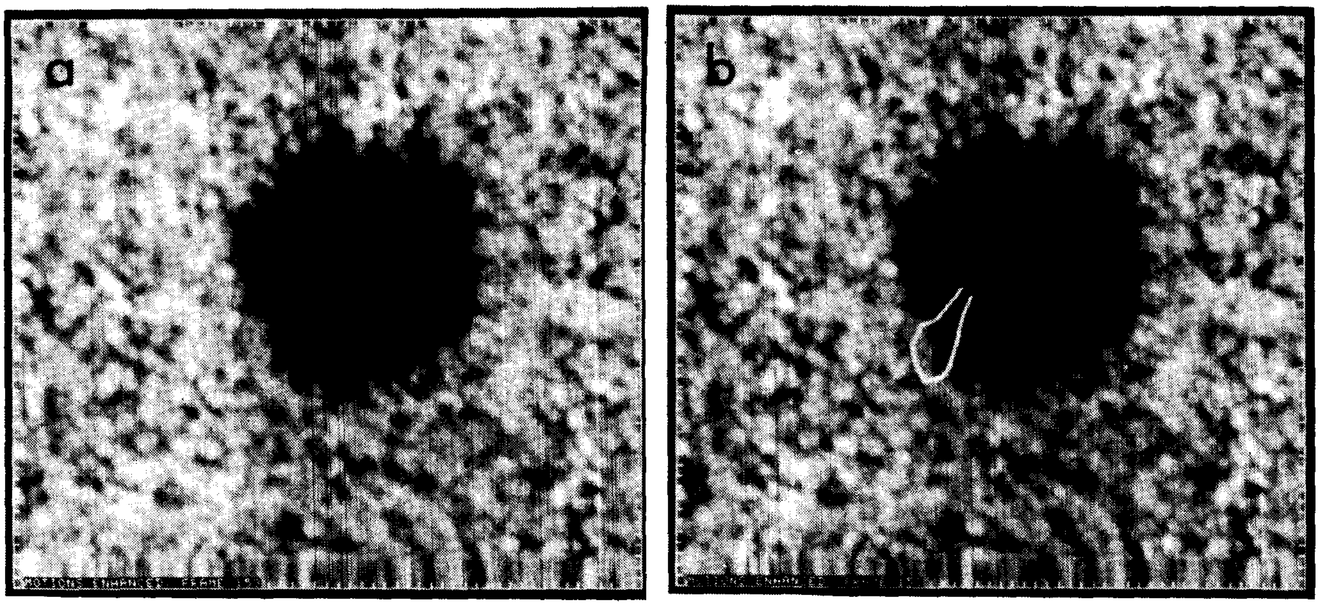

Fig. 5 (a) A single frame from a movie filtered to enhance motions with phase velocities between 2 and 4 km/s. (b) The same image with a white line drawn to show a faint bubble or loop that seemed to be ejected from the penumbra.

that affect the filament's visibility. These waves might be photospheric p-mode oscillations or waves generated from the umbra which then propagate along the filament. The overall impression is that the filaments overlay the surrounding photosphere. The idea of an overlying penumbra seems more consistent with these rapid fluctuations. We plan some modeling to test the viability of this concept. The areas showing the most obvious changes are marked in figure 1 and can be seen in the series of images in figure 2.

Often, as precursors to the filament extensions, there are photospheric brightenings in the boundaries of the regions into which the filaments extend. This is consistent with a wave scenario in which a particularly high amplitude p-mode oscillation (these have a typical spatial coherence of 10″ or more) causes the photosphere to brighten and subsequently causes the density in a nearby overlying filament to increase (thereby increasing its opacity and making it appear darker).

Possible Long Extensions: In addition to the more modest extensions described above, there may be fainter extensions of some filaments of tens of arc seconds. These are indicated in figure 1 and are visible in the later images in figure 2. These are very faint and, as figure 2 and the movies show, variable in visibility. It is unclear if they are above or within the photospheric granulation but we favor the former opinion. Their variable visibility could be the same mechanism for the shorter extensions; i.e., large scale pressure waves. The extensions may be similar to a larger class of variable linear and arc-like structures seen in the data, all of which may be density increases in overlying magnetic flux tubes.

3.5 Penumbral Motions

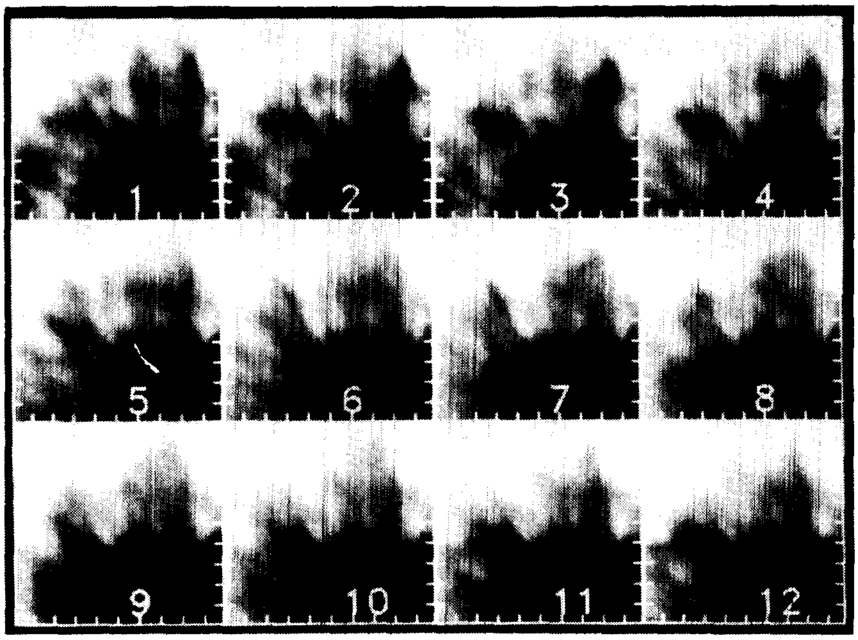

Fig. 6 A series of images showing time variations in a portion of the penumbra. The frames are 2 minutes apart and the tick marks are spaced at 1 arc second intervals.

Flow maps made by local correlation tracking (figure 4) indicate that the entire penumbra flows radially outward with velocities in the range of 100 to 400 meters per second. However, this result, which is smaller than typical doppler measurements of the Evershed flow, is affected by the field-of-view of the correlation tracker algorithm (4″ FWHM). It therefore represents an average over the penumbral structures and is probably also affected by the granulation outflow outside the penumbra. We plan to attempt further feature tracking with smaller aperatures. The preliminary map shows a positive divergence in the region of the penumbra. Not all of the penumbral structures move outward; some bright features (see below) are observed to move inward.

Penumbral Grains: The bright penumbral grains, at least those which are inside 0.75 of the penumbral radius, move inward toward the umbral. The rates are up to 500 m/s and tend to increase as the grain approaches the umbra. This is in agreement with earlier measurements of the motions of bright penumbral grains (Muller, 1981). A mosaic of images showing a $10'' \times 10''$ area of the penumbra and containing some moving penumbral grains is shown in figure 6.

Dark Clouds: Both movies and time slices show dark penumbral clouds which move outward. An area that shows particularly prominent ones in the movies is marked on the cartoon in figure 1. These are broad structures covering a few arc seconds, much larger than the width of the filaments and grains. They might be related to the "dark puffs" seen in the blue wing of H_α (Moore and Tang, 1975) and/or running penumbral waves.

4. Concluding Remarks

These first space-based high resolution white light movies of a sunspot have been remarkably successful in elucidating sunspot phenomena and highlight the severe handicap imposed by atmospheric seeing on visible light solar observations. However, it is clear that these data are only a tantalizing hint of what can be done with a stabilized solar telescope in space. Further space-based observations coupled with image processing systems capable of handling the large amounts of data will revolutionize solar physics and our understanding of stellar atmospheres in general.

There is still significant work remaining on these white light images to quantify the preliminary results better and hopefully discover new phenomena. From this 28 minute observation of a single sunspot, we cannot resolve the possibility that some of these phenomena occur only within a certain epoch of a sunspot's evolution or whether other phenomema occur. However, we can also use the insights we have gained from the SOUP data to re-examine ground based and balloon observations and help separate solar and atmospheric effects in these data.

Acknowledgements

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REFERENCES

Abdusamatov, H.I., and Krat, V.A.: 1970, *Solar Physics*, **14**, 132.

Beckers, J.M.: 1968, *Solar Physics*, **3**, 258.

Kinman, T.D.: 1952, *Monthly Notices Roy. Astron. Soc.*, **112**, 425.

Moore, R.L.: 1981, in L.E. Cram and J.H. Thomas (eds), *The Physics of Sunspots.*

Moore, R.L. and Tang, F.: 1975, *Solar Physics*, **41**, 81.

Muller, R.: 1981, in L.E. Cram and J.H. Thomas (eds), *The Physics of Sunspots.*

November, L., and the SOUP Team: 1987, these proceedings.

Sheeley, N.R.,Jr. and Bhatnagar, A.: 1971, *Solar Physics*, **19**, 338.

Title, A.M., Tarbell, T.D., Simon, G.W., and the SOUP Team: 1986 *Advances in Space Res.*, in press.

Title, A.M., Tarbell, T.D. and the SOUP Team: 1987, these proceedings.

Wiehr, E., Stellmacher, G., Knölker, M., and Grosser, H.: 1986, *Astr. Astrophy.*, **155**, 402.