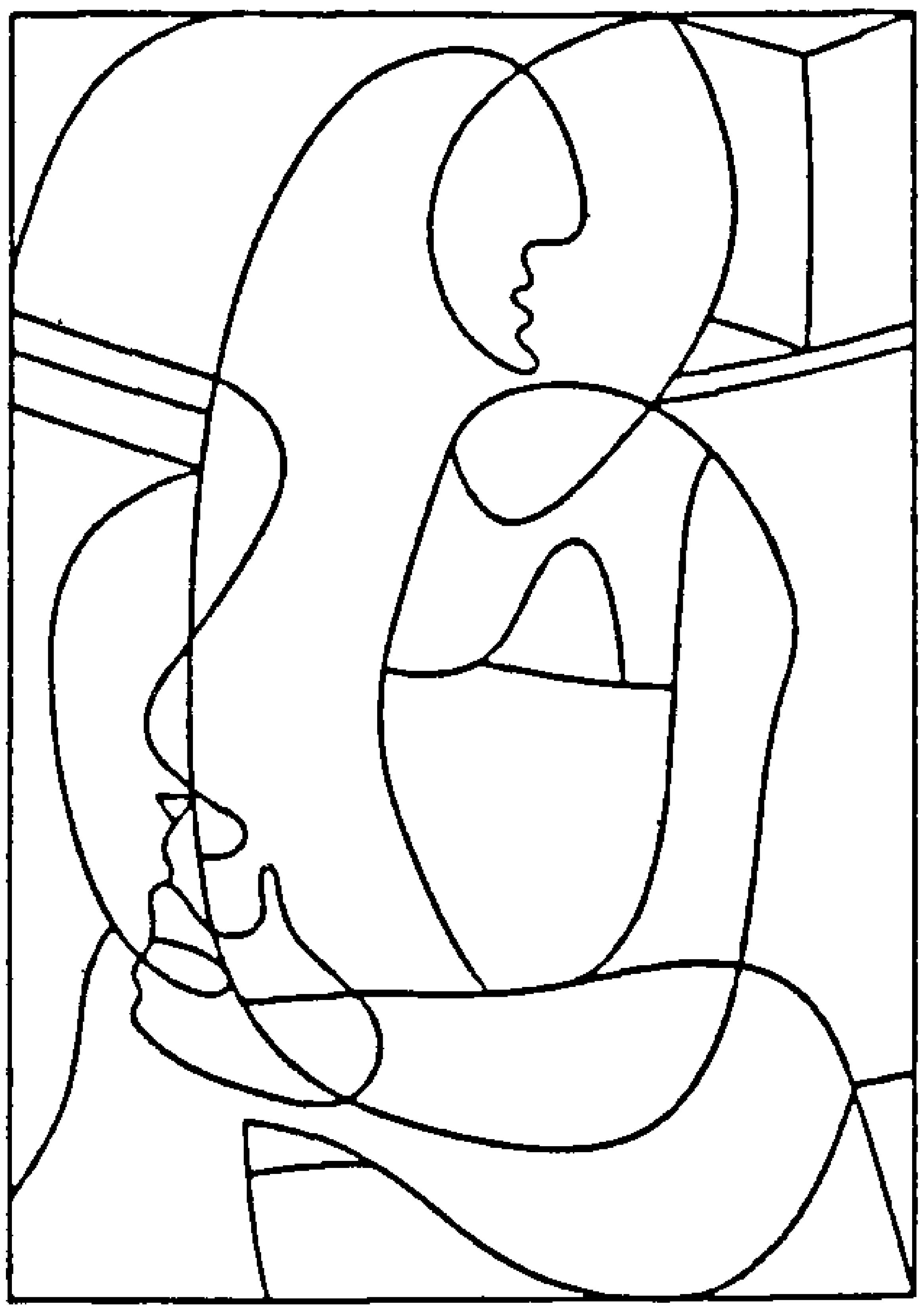

Figure 2. Picasso's drawing obeys Euler's equation as well as the cracks and space filling irregular polygonal cells do.

discussions – should be organized at different centres on a regular basis, with at least one meeting per year.

(c) Registrations for Ph D with joint supervision – one supervisor from earth sciences and another from physics – should, in due course of time, produce a new generation of earth scientists with good proficiency in the involved aspects of relevant physics ideas and tools.

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RESEARCH NEWS

Polar plumes and the solar wind: New clues from SUMER/SOHO

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Polar plumes are ray-like structures aligned along open magnetic field lines in polar coronal holes. Although apparently free to escape along open field lines, the plume gas is some 3–5 times denser than the interplume background[1,2]. This large density variation implies that the coronal heating rate is not uniform over the hole and, in particular, that enhanced energy dissipation must take place near the plume base (ref. 3 and references therein). Figure 1 shows the polar plumes and equatorial streamers.

Coronal holes are well-defined regions of strongly reduced EUV and X-ray emission in the solar atmosphere and are associated with high-speed solar wind (composed of charged particles, ions and electrons). Spacecraft measurements show that the solar wind has two components which may be described as 'slow' and 'fast'[4]. The slow wind has a speed of about 400 km/s while the high-speed wind travels twice as fast. The slow wind is an expected consequence of the corona's high temperature. It is quite variable in terms of temperature, composition, magnetic field strength, etc. and is not in equilibrium with the corona and transition layer at its base. But no one really knows what gives the high-speed wind its additional push. In contrast to the slow wind, the fast wind has the characteristics of being relatively uniform and stable. The spacecraft Ulysses also characterized two kinds of solar wind at solar minimum conditions. At high latitudes, Ulysses observed relatively smooth solar wind originating from the coronal holes in the polar regions. The fast wind departed very little from a velocity of about 750 km/s. Slow wind, at about 400 km/s and originating in the streamer belts was observed in a relatively narrow latitude band on either side of the ecliptic plane.

One can safely assume that the emission in coronal holes is low compared to the 'non-hole' corona because the plasma density and temperature at the base of the corona are reduced by the outflow in the open magnetic field

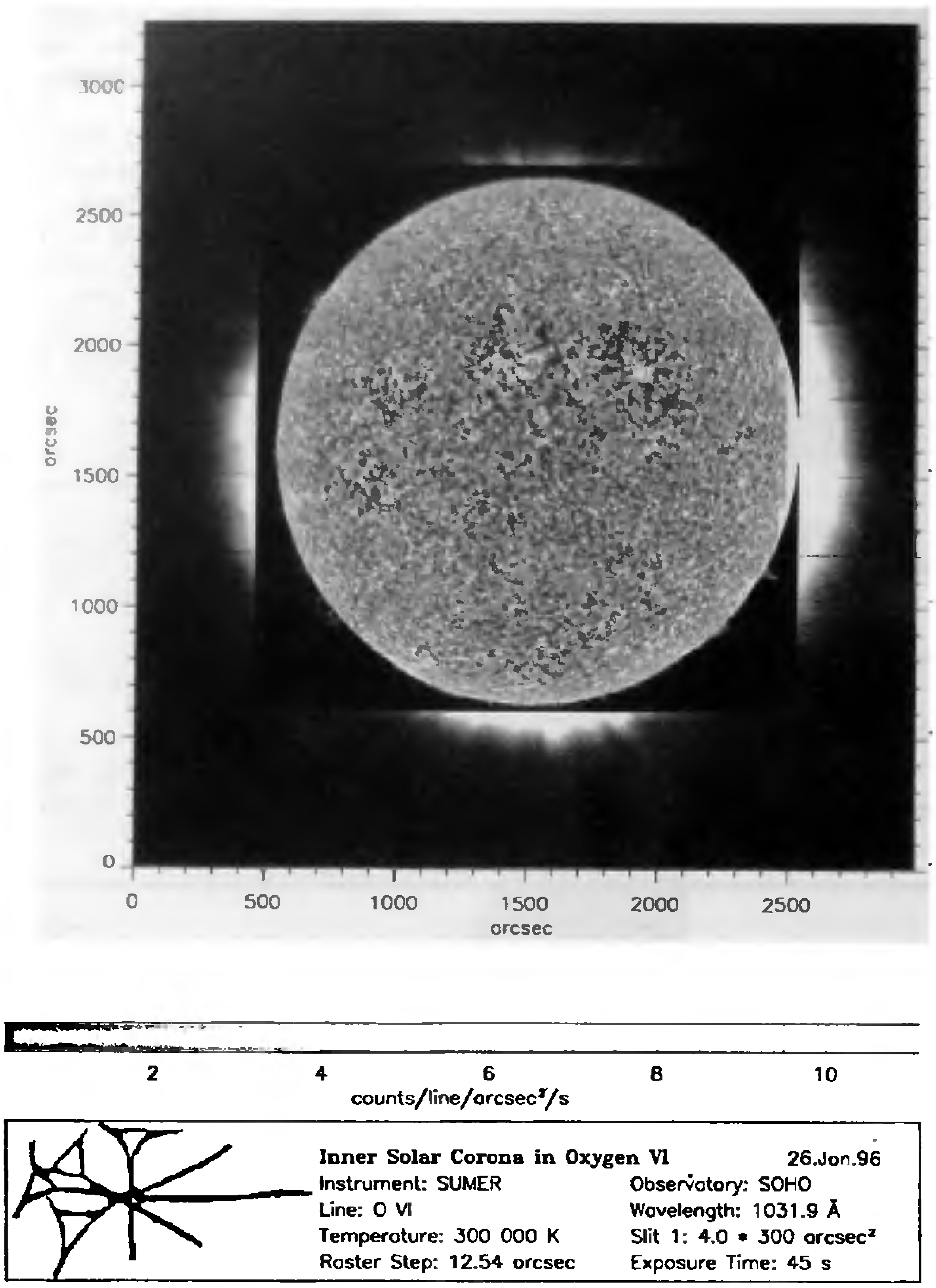

Figure 1. This composite image of the Sun and its inner corona was observed in C III line at 97.7 nm on 28 January 1996 and in O VI line at 103.2 nm on 26 January 1996. The C III image (7×10^4 K) shows the chromospheric network, some active regions and several prominences. The O VI image (3×10^5 K) clearly shows the polar plumes over the poles and indications of east and west equatorial streamers. Courtesy: SUMER/SOHO team.

associated with the coronal holes and high-speed solar wind. The inference of these quantities, namely plasma density and temperature[5], requires measurements at the limb where the foreground and background interference from the denser non-hole corona seems to be unavoidable. The corona consists of a very hot ionized gas containing free electrons. The coronal light that we see during a total solar eclipse is simply sunlight from the photosphere which has been scattered off the electrons in the corona and bent into our line of vision. The effect is somewhat similar to the scattering by tiny dust particles in a sunbeam, which renders them visible to us. The corona is best observed at X-ray and EUV spectral range not just because of the strong emission at these wavelengths but because the relatively cold photosphere essentially emits no radiation at these wavelengths. It is simply black so as to study the corona in front of such a dark disc.

During the first year of the SOHO (Solar and Heliospheric Observatory) operation, the Sun's magnetic activity was minimum between the solar cycles 22 and 23. The well-developed and relatively stable polar coronal holes provided a special opportunity to observe and scrutinize the fast solar wind acceleration region from the remote-sensing instruments on the spacecraft SOHO. Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instrument on SOHO recorded a unique set of data to investigate structures inside polar coronal holes, of which polar plumes are the most prominent ones. Jets of hot gas emanate from the Sun's north pole in an EUV (O VI at 103.2 nm) image which is one of the best SUMER images of polar plumes taken on 1996 May 21 and 22 (Figure 2).

As the only readily available, extended coronal features inside coronal holes, polar plumes provide important clues to the origin of the solar wind and heating mechanisms of its source regions. The SUMER observation of coronal holes and their interpretation call for the revision of our conventional perceptions concerning the plasma state of the corona and the source region as well as the acceleration of the fast solar wind. Consequently, we are facing a major change in 'paradigm' of the plasma physics of coronal holes and polar solar wind *vis-á-vis* the equatorial solar wind. The weakly collisional plasma is far from local thermodynamic equilibrium and the radiation signatures of excessive broadenings of heavy ion EUV emission lines reveal strong wave–particle interactions. These observations conclusively suggest cool electrons and very hot ions in coronal holes, indicating any single-fluid model completely obsolete. One of the major findings of SOHO is the observation that the fast and the slow solar wind originate and are accelerated in completely different ways.

Briefly speaking, the SUMER observations of polar coronal holes in Si VIII lines at 144.57 and 144.05 nm (ref. 6) measure via line-ratio spectroscopic diagnostics, a plasma density of 10^8 cm^{-3} at 20 arcsec (1 arcsec = 715 km on the Sun) which drops off to 6×10^7 cm^{-3} at 300 arcsec in the polar

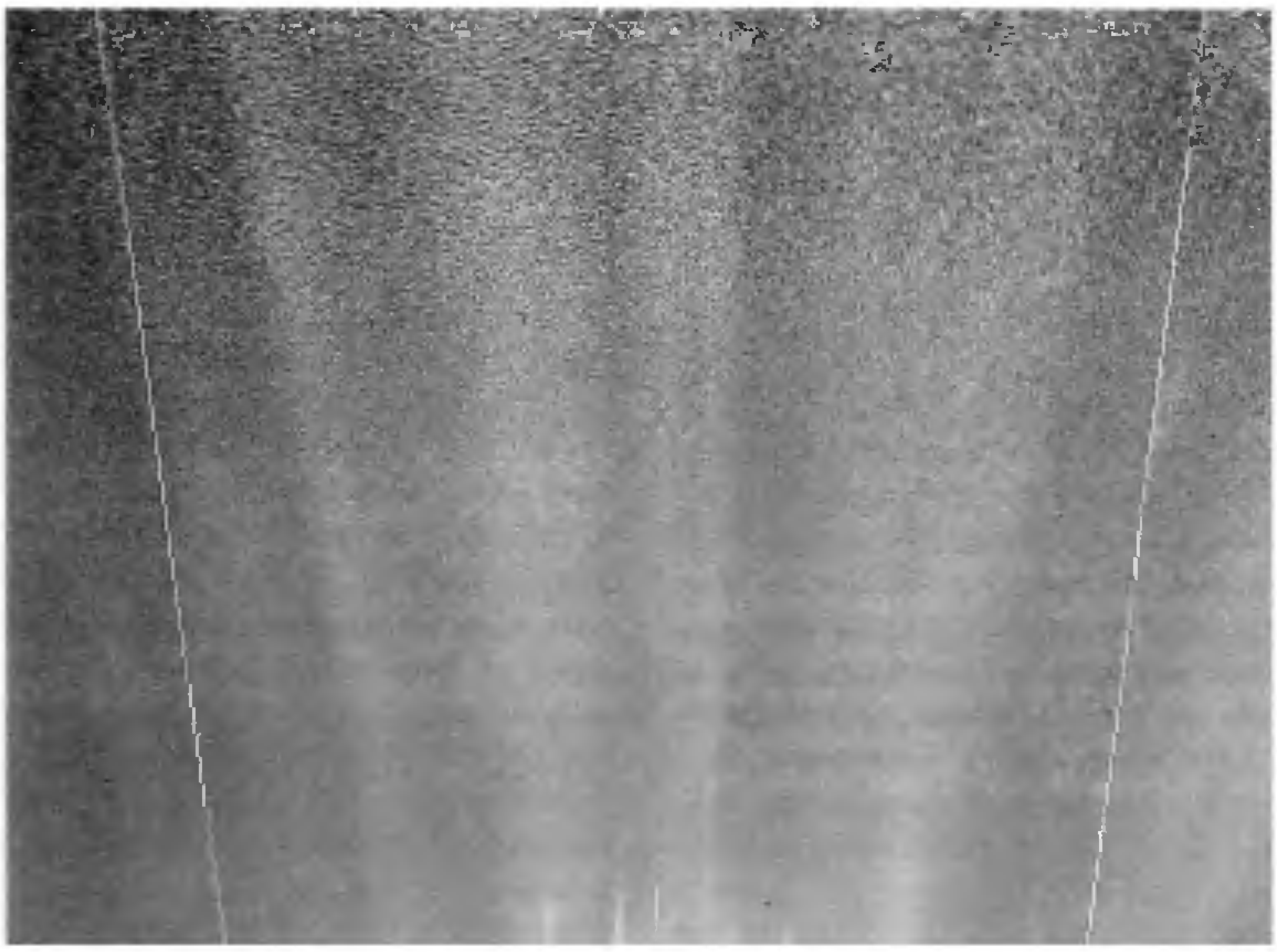

Figure 2. Polar plumes and macrospicules (spike-like jets) observed in O VI line at 103.2 nm on 21 and 22 May 1996, over the north pole of the Sun. The area shown is 380 arcsec (1 arcsec = 715 km on the Sun) in width and 285 arcsec in height. The solar limb is 30 arcsec below the lower border at the position of the short tick mark. North is up and west is right. Two radial vectors at angular pole distances of 7.5 degree are indicated. The plumes are shown in a linear scale after stray-light and flat-field corrections, and after applying a radial correction function empirically obtained by normalizing the plume west of the pole. (Image processing by G. Tomasch, MPAE, Germany.)

coronal hole. This value of density is much lower than in closed field region. Likewise, making use of temperature-sensitive line-ratio from Mg IX lines at 74.95 and 70.60 nm, an electron temperature hardly reaches the canonical value of 1 MK and remains below it and falls off rapidly with height in coronal holes[7]. Measuring O VI lines at 17.3 nm from CDS (Coronal Diagnostic Spectrometer) and 103.2 nm from SUMER instruments on SOHO, it is tentatively found that the coronal temperatures show a steep decrease, reaching about 300,000 K at $r = 1.35\,R_\odot$ ($R_\odot$ is the solar radius). Consequently, the conventional single-fluid models of coronal hole outflow are now outdated and should be replaced by multi-fluid models. Electrons are in fact largely decoupled from thermodynamics of ions. Protons and more predominantly heavy ions are rather super hot in coronal holes. Moreover, the ion temperatures are anisotropic which are interpreted as the result of ion–cyclotron heating. All these new clues are likely to play crucial role in the modelling and understanding of acceleration mechanisms of the solar wind in the entirely new perspective. Observations from the UVCS (Ultraviolet Coronagraph Spectrometer) on board SOHO, have also been the most decisive and the first to show that heavy ions have very broad profiles in polar coronal holes[8].

In summary, the major findings from SUMER observations of polar coronal holes indicate: (1) the electron temperature is less than 600,000 K in plumes which decreases with height; (2) near an inter-plume lane, the electron temperature is also low, but its height profile is almost isothermal; (3) the electron density of $10^8\,\mathrm{cm}^{-3}$ at 20 arcsec drops off to $6 \times 10^7\,\mathrm{cm}^{-3}$ at 300 arcsec; (4) line widths in plumes are narrower than inter-plume lanes; (5) the thermal and turbulent ion velocities reach values up to about 80 km/s in the darkest regions above the coronal hole which correspond to a kinetic ion temperature of 10 MK; and (6) a limit of about 18 km/s for the bulk velocity in plumes below $r = 1.2\,R_\odot$ is inferred from line shifts measurements[7].

The observation of the narrower line widths of emission lines in plumes than in inter-plume lanes, the absence of any significant motion in plumes below $r = 1.2\,R_\odot$ and high line-of-sight velocities found in dark regions above the coronal holes support the inference that the inter-plume lanes are the genuine source regions of the fast wind.

These observations provide a vital clue to the fast solar wind acceleration[9]. That is, it is the dark inter-plume lanes and not plumes from where the fast solar wind emanate. In conclusion, SUMER/SOHO observations of coronal holes provide a compelling body of evidence to revise our understanding of the source region structure and acceleration mechanisms of the solar wind. A beginning has been made but much remains to be done. And the outstanding problem of 'solar wind acceleration' may well be put in the words of the Nobel Laureate George W. Beadle: 'It's hard to make a good theory; a theory has to be reasonable, but a fact doesn't.'

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