structure of surfaces and interfaces, for example, the value of $\gamma$ and the distributed width for $\theta$.

From the reciprocity theorem, the calculation of fluorescent x-ray intensity $Y$ from coordinate $\zeta$ on the take-off angle $\theta$ is identical with that of incident x-ray field at coordinate $\zeta$ on the glancing angle $\theta$. Thus, when atoms act as fluorescent x-ray sources with a distribution $N_z$, the yield $Y$ should be

$$Y(\theta) = \int \left( I(\theta_0, \lambda_0, 2\theta) \right) N(\zeta, \sigma) d\zeta$$

where $I(\theta_0, \lambda_0, 2\theta)$ is the primary x-ray intensity, which is affected by the total reflection beam for the incident wavelength $\lambda_0$ at coordinate $\zeta$. The distribution $N(\zeta, \sigma)$ reaches a maximum at $\zeta = z_0$ and is assumed to be a Gaussian distribution with standard deviation $\sigma$ (see Fig. 2). The intensity $I(\theta, \lambda_0, 2\theta)$ for fluorescent x-ray wavelength $\lambda_0$ results from interference between the direct and totally reflected fluorescent emissions at coordinate $\zeta$.

We obtained $z_0$ and the width $2\sigma$ for $x^2$ minimization fit for $Y(\theta)$. The theoretical FXI pattern is in close agreement with the experimental one (Fig. 4). The values of the refractive indices of the gold substrate and of the LB film were obtained from the corresponding four wavelengths.

Thus, our value of $2\sigma$ is in close agreement with the value of the short axis for BSA (Fig. 4B), $2\sigma_{\text{BSA}} = 63 \pm 21 \text{Å}$ and $2\sigma_{\text{Fe}} = 58 \pm 16 \text{Å}$. The form of the BSA molecule, based on electron microscope observation with a metal coating (9), is a prolate ellipsoid with a major axis $2a = 140 \text{Å}$ and a minor axis $2b = 40 \text{Å}$. This value of $2\sigma_{\text{Fe}}$ is in close agreement with the value of the short axis for the BSA molecules. Consequently, the experimental FXI pattern is consistent with a model in which the short axes of BSA molecules are perpendicular to the surface of the substrate.

The major hindrance to the removal of these inconsistencies and uncertainties, the lack of high spatial resolution infrared instrumentation, has been overcome recently with the installation of a large infrared grating on the main spectrograph of the McMath-Pierce facility at Kitt Peak, near Tucson, Arizona. Spectra at 4.67 $\mu$m were obtained in April 1993 at the solar limb under conditions of exceptionally low smearing by the Earth’s atmosphere and low atmospheric water vapor (Figs. 1 and 2). Outside the continuum limb the CO spectrum is clearly in emission.

From the observed continuum limb profile we first determined the spatial smearing due to the finite telescope aperture, spectrograph slit width, atmospheric blurring, and scattered light, assuming a regular limb. The observations were best reproduced without any atmospheric blurring. Perhaps a quiescent “random walk” atmosphere prevailed (7). We then used the inferred smearing and scattering parameters to estimate the true limb profile of the CO line core emission (Fig. 3). The brightness temperature of the optically thick CO line cores remains constant at 3600 to 3900 K to approximately 0.4 arc sec outside the 4.7- $\mu$m continuum limb (corresponding to the key properties—particularly the horizontal and vertical extents—are highly uncertain (6).

Solar carbon monoxide spectra indicate the existence of a cool (less than 4000 kelvin) component to the solar chromosphere coexisting with the hot, bright gas at 6000 to 7000 kelvin. However, both the existence and the location of the cool component have been controversial. New high-resolution spectra show that carbon monoxide goes into emission just beyond the limb, allowing it to be probed without photospheric contamination. The cool component has temperatures as low as 3000 to 3500 kelvin and appears to cover 50 to 50 percent of the quiet solar surface. There is a steep temperature rise to normal chromospheric temperatures at a height of 900 to 1100 kilometers. Large horizontal velocities are seen, suggesting that the cool component is maintained by the supersonic adiabatic expansion of upwelling gas in overshooting granules.

REFERENCES AND NOTES

13. The authors thank Y. Tomioka for preparing the sample, A. Fukuhara for discussion, S. Imazeki for advice about charged LB film, and K. Kina for advice about labeling protein. This study was performed under the approval of the National Laboratory for High Energy Physics (proposal no. 93-Y003).

25 August 1993; accepted 29 October 1993

New Light on the Heart of Darkness of the Solar Chromosphere

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The chromosphere of the sun is prototypical for the chromospheres of most cool stars. Any major challenge to the understanding of its structure will accordingly reverberate through many areas of solar and stellar physics. We report here on observations that strongly support the need for a fundamental revision of the traditional picture of the chromosphere as a relatively homogeneous thermal structure, with a temperature lying between 5000 and 7000 K over most of its height (1). Models based on this picture reproduce an impressive array of observations, mainly atomic spectral lines and continuum spectra, but possess one major flaw. They cannot match observations of the fundamental vibration-rotation band of the CO molecule at 4 to 5 $\mu$m (2). On the other hand, previous models based on the CO lines (2, 3) cannot be easily reconciled with the traditional optical and ultraviolet diagnostics. This inconsistency has led some researchers to doubt the very existence of a cold component (4, 5), and there is general agreement that its...
mental smearing is quite forgiving in this case, and in the core of the 3–2 R 14 transition. The thick curves have been derived empirically from the observations. The thin curves represent the limb profile in the core of the CO line resulting from single component models VALC and 35COLD13.

Nevertheless, our numerical experiments suggest that 25 to 50% of the solar surface is covered by a steep temperature rise at \( T = 3000 \) km, while 25 to 35% is covered by such a rise at \( T > 1000 \) km. An upper limit on \( T \) cannot be given because the limb profile of CO emission does not react significantly to large values of \( T \). We conjecture, however, that \( T \) does not significantly exceed 1000 km over almost the whole solar surface, because at heights above approximately 1200 km most of the chromospheric volume apparently is hot according to far-ultraviolet emission of O I and C I (5).

The CO fundamental band lines belong to the few off-limb tracers of the chromospheric gas that can be satisfactorily reproduced by hydrostatic models (11, 12). This relation supports the view that highly dynamic phenomena, such as spicules, which extend the chromospheric emission upward, are restricted to the hot (and probably magnetic) part of the chromosphere. Nevertheless, the CO lines support the presence of considerable dynamics in the cool component. The optically thin off-limb emission lines, which form purely in

**Fig. 1.** Selected spectra observed near the north solar limb while the entrance slit was stepped across the solar limb at intervals of 0.3 arc sec. The upper spectrum lies inside the solar limb, exhibits absorption lines, and refers to the axis on the left. The lower spectrum lies outside the limb and refers to the right axis. The three main CO features are identified; the line marked with \( T \) is produced in the Earth's atmosphere. The off-limb spectrum exhibits emission features at the same wavelength as the CO absorption lines on the disk. The expression \( I / D \) denotes the intensity normalized to the continuum intensity at the center of the solar disk.

**Fig. 2.** Observed and synthesized profiles of the solar limb at a wavelength in the continuum and in the core of a CO transition. Negative spatial positions correspond to the solar disk. The origin of the spatial axis corresponds to optical depth unity at 5000 Å. An increase in the CO core emission begins to drop, for example, an increase in \( T_H \), the temperature at which the emission begins to drop, and the “emission folding” width, \( \Delta Z_c \), of the drop in emission beyond \( Z_c \).

**Fig. 3.** Temperature versus geometrical height of four representative models. A geometrical height of 0 corresponds to spatial position 0 in Figs. 2 and 3.
the chromosphere, exhibit a significantly larger broadening than the absorption profiles on the disk (2 to 3 km s⁻¹) (2, 13).

The large horizontal velocities implied by these excess line widths are reminiscent of the almost adiabatically expanding cool gas overlying granules in the upper reaches of granular simulations (14). Our observations suggest that on the real sun the convective overshoot does not stop at the temperature minimum, as is tacitly assumed in practically all current granular simulations, but continues into the lower chromosphere. In addition, the horizontal supersonic velocities seen in recent numerical simulations of solar convection (15, 16) are possibly common in the dark heart of the lower chromosphere. One interpretation of the observations is that the CO lines form mainly in the granule centers, upstream of the shock fronts located near the downflow lanes. Hence, although the CO limb emission is well reproduced by hydrostatic atmospheres, the influence of convective dynamics on the stratification of the cool gas should be carefully investigated.

This cold chromospheric component survives even in the presence of substantial acoustic energy deposition (except at locations where the heating is particularly intense, such as magnetic elements) because of a combination of CO radiative cooling (17) and adiabatic expansive cooling. Energy deposition produces a hot thermal zone overlying the cool layers (4, 18). The magnetic field, which produces a magnetic canopy with a base close to Z⊙ (19), probably tends to stabilize the location of the steep rise of the temperature at the top of the heart of darkness of the solar chromosphere.

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5 November 1993; accepted 24 November 1993

**Void Structure in Colloidal Dispersions**

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The time evolution of void structures in highly purified polymer latex dispersions was studied with a confocal laser scanning microscope. In such dispersions, which were initially simple ionic solutions, ionic polymer solutions, and Langmuir-Blodgett films.

**Dilute polyelectrolyte solutions give a single, broad peak in the small-angle x-ray scattering profile which is attributed to the formation of an ordered structure (1). Although this interpretation of the peak was substantiated by a theoretical calculation of the scattering function by Matsuoka et al. (2, 3), we were left with the intriguing result that the Bragg spacing between macroions in the ordered structure (2Dₓₑₓ) (experimental uncertainty of order ±10%) was much smaller than the theoretical average spacing (2Dₓ) expected from the overall macroion concentration. For example, a fractionated sodium polycrylate with 1470 monomer units had a 2Dₓₑₓ value of 88 Å at a polymer concentration of 0.02 g/ml and 22°C, whereas the theoretical 2Dₓ was 222 Å. The same trend was observed for various ionic polymers, including highly charged globular proteins.

According to a simple stoichiometric consideration, the difference between the two spacings indicates that localized, non–space-filling ordered structures exist. The total sum of the volumes of these ordered structures must be 0.06 [≈(88/222)] of the solution volume (although the volume of the single localized structure is not known), leaving 94% of the solution volume occupied by disordered macroions or voids. The coexistence of the ordered structure and free macroions appears to be supported by observation of slow and fast diffusion modes by dynamic light scattering (4).

Independently, Hachisu et al. (5) successfully observed under microscope void structures in dispersions of ionic polymer latex particles. This observation was confirmed by two groups (6–8), which reported huge and stable voids in apparently homogeneous dispersions. Voids were stable over about 10 hours and were observed even in samples several months old (7). Thus, we decided that the void structure must be considered if the true nature of interparticle interactions is to be sought. To eliminate the effect of the glass-dispersion interface (wall effect) in the void formation, we (9) used a confocal laser scanning microscope, which allowed observation of particles at a greater distance from the interface than previous microscopes (for example, even at 700 μm in a latex concentration of 0.01% for polystyrene-based particles in a D₂O-H₂O mixture). We found that huge, stable voids existed in the interior of the dispersion. Voids as large as 50 μm by 150 μm by 50 μm have been photographed (10).

The implication of the existence of such large and stable voids has recently been discussed (10). The voids testify to the presence of an attractive interaction between the colloidal particles. Here we describe a preliminary study of how the void structure in latex dispersions changed with time and depth from the top of the dispersion. A similar structural inhomogeneity, in apparently homogeneous systems, is discussed for simple ionic solutions, ionic polymer solutions, and Langmuir-Blodgett films.

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5 November 1993; accepted 24 November 1993

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