THE HARVARD-SMITHSONIAN REFERENCE ATMOSPHERE

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Abstract. We present a model of the solar atmosphere in the optical depth range from $\tau_{5000} = 10^{-8}$ to 25. It combines an improved model of the photosphere that incorporates recent EUV observations with a new model of the quiet lower chromosphere. The latter is based on OSO 4 observations of the Lyman continuum, on infrared observations, and on eclipse electron densities.

Our model differs from the Bilderberg Continuum Atmosphere (BCA) in the low chromosphere ($\tau_{5000} < 10^{-4}$), where deviations from local thermodynamic equilibrium in hydrogen and carbon have been taken into account. It also differs in the transition region between the chromosphere and the photosphere ($10^{-4} < \tau_{5000} < 10^{-3}$), where the temperature is lower than in the BCA, and in the convective region ($\tau_{5000} > 2$), where the temperature is higher than in the BCA.

1. Introduction

Empirical solar model atmospheres have traditionally used limb-darkening measurements as the means for probing different layers of the Sun’s atmosphere, but a far more powerful technique became available with the advent of absolute-intensity determinations over a wide wavelength region. Because of the large opacity in the infrared and ultraviolet, the solar temperature structure can be examined through the temperature minimum and into the low chromosphere by means of continuum observations alone. One model to exploit this procedure extensively was the Bilderberg Continuum Atmosphere (Gingerich and de Jager, 1968), hereafter referred to as the BCA model. Since the time it was prepared, critical new observations have been obtained from above the earth’s atmosphere, and these permit a significant improvement of the BCA model.

Rocket observations obtained in September 1968 by Parkinson and Reeves (1969) and again in 1970 include the particularly interesting ultraviolet region around 1650 Å, where the radiation arises from the coolest layers of the solar atmosphere. The brightness temperature they obtain there is below 4400 K, in contrast to the 4600 K minimum of the BCA. Their measured brightness temperature is also about 300 K below that measured by Widing et al. (1970); this difference corresponds to a factor of 3 change in absolute intensity. The source of the discrepancy is not yet determined.

However, independent evidence for a lower temperature minimum has been reported by Eddy et al. (1969b). Their airborne observations made at about 300 μ yield a brightness temperature of about 4300 K. The limb-darkening observations

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Variation of temperature with optical depth $\tau_{5000}$ for three model solar atmospheres. The physical depth scale $h$ (km) is the height above $\tau_{5000} = 1$ for the HSRA model.

of Léna (1970) at 10 $\mu$ and 20 $\mu$ provide additional evidence in this direction. Furthermore, analysis of the H and K line profiles seems to demand a lower temperature minimum, near 4300 K (Linsky and Avrett, 1970).

In light of these new observations, a preliminary revision of the BCA, calculated entirely with the assumption of local thermodynamic equilibrium (LTE), was presented at the Pasadena Solar-Physics Meeting of the American Astronomical Society in February 1969, and copies of that model, known as SAO 5, were distributed to a few investigators. It represented an attempt to drive to its ultimate limit a single-stream, LTE solar model. The Harvard-Smithsonian Reference Atmosphere (HSRA), shown in Figure 1, is a somewhat improved version. It differs from the SAO 5 for layers above $\tau_{5000} = 10^{-5}$; in this model, the temperature minimum is slightly deeper, the low chromospheric temperatures have been adjusted in the light of Cuny's (1971) non-LTE calculations, and the temperature in the chromospheric layers above $\tau_{5000} = 10^{-5}$ has been determined by Noyes and Kalkofen (1970) with the hydrogen populations in statistical equilibrium (non-LTE).

The BCA was characterized by a broad temperature plateau extending from $\tau_{5000} = 10^{-2}$ to $10^{-4.5}$; this seemed necessary in order to reproduce the observed absence of limb brightening or darkening around 1650 Å. However, the gentle downward temperature gradient of the present model still agrees with the rather qualitative center-to-limb observations around 1650 Å. In this model, the temperature minimum is reached only at $\tau_{5000} = 10^{-4}$, and the minimum zone is so narrow that its radiation cannot be investigated independently of the hotter surrounding layers. In other words, the actual minimum of 4170 K is a somewhat arbitrary choice, not well determined (see Figure 1).

The HSRA differs from the BCA in another important respect. In the deepest layers, where the model is convectively unstable, this model has temperatures several hundred degrees hotter, consistent with a mixing-length theory of convection. The problem of establishing these temperatures is intimately connected with the difficult and unresolved question of the ultraviolet opacity; it will be discussed in Section 4B.

In the remainder of this paper we discuss the observational data that have led us to