THE ASTROPHYSICAL JOURNAL, Vol. 152, April 1968

THE STATE OF IONIZATION OF OXYGEN IN THE SOLAR WIND

A. J. HUNDHAUSEN, H. E. GILBERT, AND S. J. BAME
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received January 15, 1968

The continuous expansion of the solar corona, leading to the "solar wind" of Parker (1963), has been directly observed on many satellites and space probes (e.g., Gringauz *et al.* 1963; Bonetti *et al.* 1963; Snyder and Neugebauer 1964). The ionic component of the solar wind has been shown to consist largely of H^+ with a highly variable admixture (0 per cent to 15 per cent) of He^{+2} (Neugebauer and Snyder 1966; Hundhausen *et al.* 1967).

High resolution measurements of the positive ion energy per charge spectra, made on the Vela 3 satellites, have also revealed the presence of oxygen ions in the solar wind (Bame *et al.* 1968). Under the low-temperature conditions requisite for resolution of the closely spaced spectral peaks corresponding to the various ions of oxygen, O^{+6} is usually found to be more abundant than either O^{+5} or O^{+7}. A few cases have been found in which O^{+7} is the most abundant oxygen ion.

It is the purpose of this Letter to point out that the ionization state of a given element is established deep within the corona and is little affected by the expansion of the coronal material to 1 a.u. Thus the ionization state observed at the latter distance is a direct indication of the temperature of the corona. This is in contrast with other quantities measured in the solar wind, such as flow velocity, density, or particle temperatures, which depend strongly on the details of the coronal expansion.

Consider, for example, O^{+6} and O^{+7}, the two most abundant oxygen ions at the coronal temperature of $\sim 10^6$ ° K (see Tucker and Gould 1966). The O^{+7} ions are produced by collisional ionization of O^{+6}, and lost by radiative and dielectronic recombination to O^{+6} (photo-ionization and three-body recombination are negligible; see Billings 1966, p. 129). Thus the net rate of production of O^{+7} in a unit volume is

$$C_6 n_6 n_e - R_7 n_7 n_e ,$$

where n_6, n_7, and n_e are the number densities of O^{+6}, O^{+7}, and the electrons, respectively; C_6 is the collisional ionization rate for O^{+6}; and R_7, the total (radiative plus dielectronic) recombination rate for O^{+7}. In a static corona the net production rate must be zero in the steady state, and $n_6/n_7 = R_7/C_6$, a function of temperature only.

In a non-static system, such as the expanding solar corona, the net rate of production of an ion species need not be zero, as a steady state can be maintained by allowing ions formed in any volume element to flow out. The conventional static approximation is valid only when the scale times for the ionization and recombination processes are much less than the scale time for the expansion. Figure 1 shows the scale times $\tau_6 = (n_e C_6)^{-1}$ for the collisional ionization of O^{+6}, $\tau_7 = (n_e R_7)^{-1}$ for recombination of O^{+7}, and $\tau_e = [|ud(\ln n_e)/dr|]^{-1}$, the time for the material to flow through one density scale height, in the corona. Values of coronal density, temperature, and expansion velocity have been taken from the model corona of Whang and Chang (1965), and the rates C_6 and R_7 adopted from Tucker and Gould (1966). Note that beyond a heliocentric distance of $\sim$1.2 solar radii, $\tau_e < \tau_6$ or τ_7, so that the static approximation will break down and the flow of the ions must be taken into consideration in the computation of the state of ionization. Indeed, the solar wind transports coronal material to 1 a.u. in $\sim$4 days or $\sim 4 \times 10^5$ sec. Beyond $\sim$1.7 solar radii τ_6 and τ_7 are both greater than the transit time

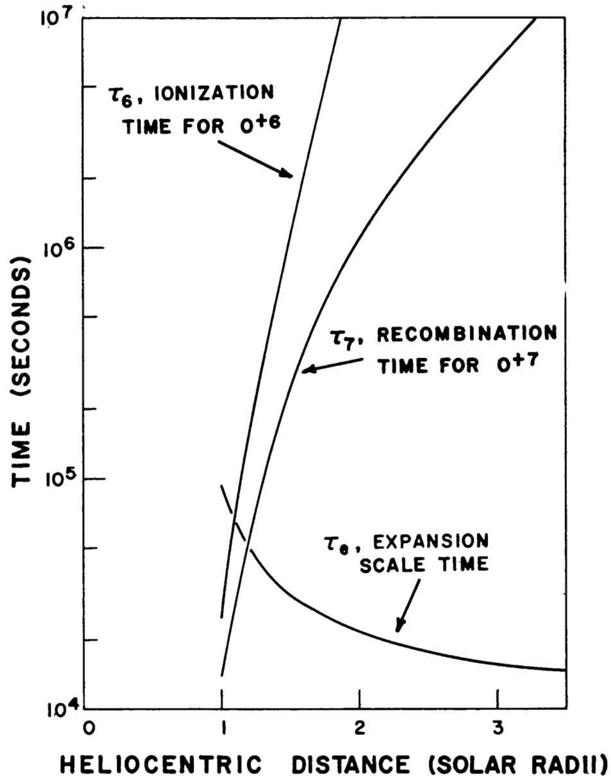

FIG. 1.—The scale times: τ_6 for ionization of O^{+6}, τ_7 for recombination of O^{+7}, and τ_e for expansion through one scale height of density. The coronal model of Whang and Chang has been used to give density, temperature, and flow velocity as a function of heliocentric distance.

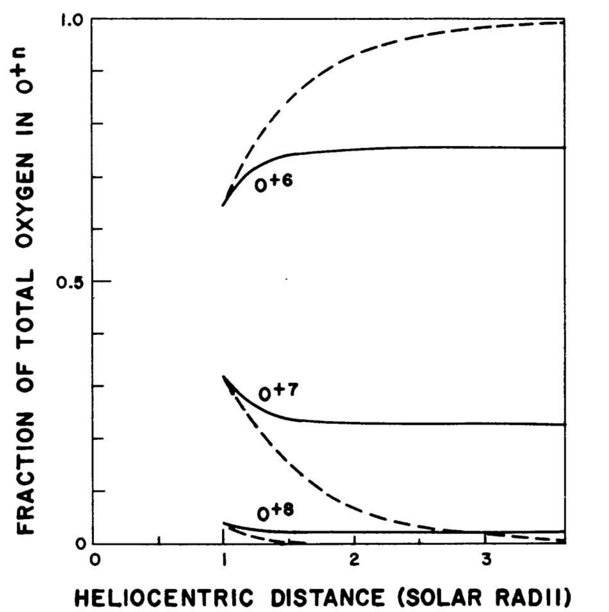

FIG. 2.—The fraction of oxygen present as the ions O^{+6}, O^{+7}, and O^{+8} for (1) the dynamic model, including the effects of coronal expansion (*solid lines*), and (2) the conventional static model (*dashed lines*), as a function of heliocentric distance.

to 1 a.u., and it is clear that little change can take place in the state of ionization in the expansion beyond this radius.

To put this argument on a quantitative footing, the set of coupled ionization equations

$$\nabla \cdot n_i u = C_{i-1} n_e n_{i-1} - (C_i + R_i) n_e n_i + R_{i+1} n_e n_{i+1}$$

has been numerically integrated for oxygen ions from O^{+5} to O^{+8}. The divergence term on the left-hand side of the ith equation gives the flow of the ith ion out of a volume; the right-hand side is the rate of production of the ion in the volume. Again the Whang and Chang coronal model and the Tucker and Gould ionization and recombination rates have been used. The solid lines in Figure 2 show the fraction of oxygen present as O^{+6}, O^{+7}, and O^{+8} (the O^{+5} fraction is negligible) as a function of heliocentric distance. The ordinary static solution was assumed at the base of the corona, $r = 1$. The dashed line shows the static solution for the temperature as a function of heliocentric distance implied by the Whang and Chang model. As expected, the state of ionization begins to deviate from that given by the static solution shortly above the base of the corona, and it does not change significantly beyond $\sim$1.7 solar radii.

It is thus clear that the state of ionization of an element measured at 1 a.u. is the same as that established deep in the corona. The ratio n_6/n_7 obtained for large heliocentric distances in the calculation described above is consistent with estimates of this ratio based on the Vela 3 measurements. The temperature at the base of the corona in the Whang and Chang model is 1.58×10^6 ° K. The ion O^{+7} will be more abundant than O^{+6} only when the coronal base temperature is above 2.2×10^6 ° K. Thus the Vela measurements indicate that the coronal temperature is usually below 2×10^6 ° K (for the conditions under which resolution of O^{+6} and O^{+7} is possible), but in a few cases it is above this value (perhaps only locally).

Measurements of solar wind, such as these, offer a new means of obtaining the coronal temperature. The results of the calculation shown in Figure 2 also demonstrate that the state of ionization of an element deep within the solar corona can deviate from that predicted by the conventional static model. Thus the state of ionization, derived spectroscopically, may not be interpretable in terms of the local temperature, even at a few tenths of a solar radius above the base of the corona (see Delache 1965).

This work was performed under the auspices of the U.S. Atomic Energy Commission.

REFERENCES

Bame, S. J., Hundhausen, A. J., Asbridge, J. R., and Strong, I. B. 1968, *Phys. Rev. Letters*, **20**, 393.
Billings, D. E. 1966, *A Guide to the Solar Corona* (New York: Academic Press).
Bonetti, A., Bridge, H. S., Lazarus, A. J., Lyon, E. F., Rossi, B., and Scherb, F. 1963, *Space Res.*, **3**, 540.
Delache, P., 1965, *C.R.*, **261**, 643.
Gringauz, K. I., Bezrukikh, V. V., Balandina, S. M., Ozerov, V. D., and Rybchinskly, R. E. 1963, *Space Res.*, **3**, 602.
Hundhausen, A. J., Asbridge, J. R., Bame, S. J., Gilbert, H. E., and Strong, I. B. 1967, *J. Geophys. Res.*, **72**, 87.
Neugebauer, M., and Snyder, C. W. 1966, *J. Geophys. Res.*, **71**, 4469.
Parker, E. N. 1963, *Interplanetary Dynamical Processes* (New York: Interscience Publishers).
Snyder, C. W., and Neugebauer, M. 1964, *Space Res.*, **4**, 89.
Tucker, W. H., and Gould, R. J. 1966, *Ap. J.*, **144**, 244.
Whang, Y. C., and Chang, C. C. 1965, *J. Geophys. Res.*, **70**, 4175.