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The Temperature of the Solar Corona

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Abstract. This paper is a historical survey of the temperature determinations in the solar corona. After the description of the early results, it focuses on coronal holes; it discusses the discrepancies of the past and comments on the nearly general present agreement.

Key words. Solar Corona – Temperature

1. Introduction

The temperature of the solar corona has been a quite interesting scientific puzzle, and even now it retains some of its mystery because not all the indications converge. In this paper I review the temperature determinations which have been made, from the early ones up to the recent times. I will not include the ones based on the scale height of the coronal material, because I find them the less reliable, owing to the presence of the magnetic field.

2. Early determinations

2.1. Observations in the visible

The scientific exploration of the solar corona can be considered to begin with the 1842 total eclipse of the Sun: the main aim of the observers, at that eclipse, was to establish whether chromosphere, prominences and corona were solar features or phenomena of the Earth atmosphere. The solution of the problem came only many years later: Janssen (1879), from the stability of the coronal image during the 1871 total eclipse, concludes that the corona is indeed solar. Also, at that eclipse, there was a first hint, in the data, of the high temperature of the corona, because Lockyer and Respighi (Respighi 1872) observed that the green line emission extended to great heights. The significance of this was not understood and this result posed a dynamical problem, since the coronal temperature was thought, at that time, to be much smaller than we know now. Another strong indication of the high coronal temperature came with the 1929 eclipse, in which photometric spectra of the coronal radiation were obtained by Grotrian. Grotrian confirmed previous results that the spectral distribution of the radiation of the low corona was the same as that of the photosphere, which was strongly in favor of the idea that it was due to scattered photospheric radiation, and also pointed out that the oblit-

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eration of the Fraunhofer lines (only the H and K calcium lines could be identified as a shallow, very wide depression between 3700 and 4000 Å) implied that the velocity dispersion of the scattering particles (free electrons) was very large, more than an order of magnitude larger than that corresponding to the temperature of the photosphere (Grotrian (1931)).

A breakthrough in the coronal studies was the invention of the coronagraph (Lyot (1932)), which permitted to observe the inner corona outside eclipses, although no information on the coronal temperature could be obtained from the line widths (measured by Lyot and others) since the lines were not identified. The real discovery of the high temperature of the coronal gas came with the identification of the emission lines. In 1939 Grotrian identified two lines as produced by the Fe X and Fe XI ions, and in 1942 Edlèn identified almost all the other coronal lines. These also turned out to be due to transitions in many times ionized atoms, which implied that the coronal temperature had to be very high. Its value, however, was difficult to establish since the cross sections needed to calculate the ionization state were poorly known. Edlèn, in his line identification paper, assumed the value $T = 250000$ K.

Once the lines of the coronal spectrum had been identified, and thus the mass of the emitting ion was known, the temperature could be deduced from the line widths. These were measured by Dollfus (1953), with the use of a Lyot coronagraph, and the temperature obtained was $T_{ion} = 1.7 - 2.5 \times 10^6$ K. For what concerns the temperature transition from the chromosphere to the corona, Giovannelli (1949), on the basis of eclipse observations, found a very large temperature gradient, and pointed out the importance of thermal conduction in the energy balance of the coronal base. The Woolley and Allen model, conduction dominated in the chromosphere-corona transition region, has, indeed, a very fast temperature increase in this region (Woolley and Allen (1950)).

In the following years it became apparent that the temperatures deduced from ionization balance calculations and radio data (see next section) were significantly smaller than those deduced from the line widths (van de Hulst (1953)). An improved estimate of the ionization cross sections by electron impact (Elwert (1952)) confirmed this, giving $T_e(ib) \simeq 8 \times 10^5$ K, and new theoretical calculations (and experimental data) concerning the relevant cross sections reinforced this result (Burgess (1960); Seaton (1960)). Also the study of individual ions gave systematically $T_e(ib)$ quite smaller than T_{ion} (Seaton (1962)). Note that $T_e(ib)$ is an electron temperature, because the ionizations, in coronal conditions, occur via electron collisions, hence both processes, ionization and recombination, depend on the velocity distributions of the electrons. T_{ion}, instead, being deduced from the line widths, depend on the velocity distribution of the ions, and includes the macroscopic motions, which may be due to waves, turbulence, etc. Hence T_e and T_{ion} may be different, not only because of macroscopic motions, but also in presence of preferential heating, if the density is not high enough to equalize the 'atomic part' of the temperatures through the collisions (which occurs at rather low heights in the solar corona).

2.2. Radio observations

Radio observations are another mean to determine the temperature of the solar corona. After the discovery that the solar corona is a radio emitter, it was soon clear that the emission included two thermal components (the 'Quiet Sun' and the 'Slowly Varying' or S components), due to the free-free and free-bound transitions of the electrons. For the coronal sources of the S-component (regions of increased density associated with sunspots) a temperature of a few million degrees was found; for the quiet sun component the temperature turned out to be smaller. For this emission the brightness temperature, T_b, is connected to the electron temperature by the equation

$$T_b = \int_0^{2\tau_m} T_e d\tau \quad (1)$$

where τ_m is the optical depth of the critical point and

$$d\tau = f(N_e, T_e) ds, \quad (2)$$

being f a known function and s a coordinate along the ray path. The identification of the quiet sun emission (defined as the solar emission when all the localized sources were excluded), which was not an easy task, led to a coronal temperature of $\simeq$ 700000 K. Being this value somewhat model dependent, we can conclude that

$$T_e(radio) \simeq T_e(ib) \simeq \frac{1}{2} T_{ion}. \quad (3)$$

(For the temperatures determined via radio observations, see Kundu (1965) and references therein.)

2.3. Observations on the disk in the UV spectral region

In the early sixties rocket UV data became available. With this data and ionization calculations it was possible to determine the density-temperature structure of the transition region and the coronal base (Ivanov-Kolodnyi and Nikol'skii (1961); Pottasch (1963)), as well as the chemical abundances (Pottasch (1964)). The density-temperature structure was described by the emission measure (EM) as a function of the temperature:

$$EM(T) = \int N_e^2 dh, \quad (4)$$

where N_e is the electron density and h the height above the photosphere. Since the temperature values are obtained from ionization balance calculations, the temperature of this equation is $T_e(ib)$. The result of these studies, for what concerns the temperature, was a coronal value of $\sim 1 \times 10^6$ K, which was in a reasonable agreement with the previous determinations of T_e, being the field in a still early stage. It was also confirmed that the temperature rise in the transition region was characterized by a very steep gradient.

2.4. Dielectronic recombination

An important change occurred in 1964, when Burgess realized the importance of dielectronic recombination among the processes determining the ionization state. The addition of this recombination channel sensibly increases the electron temperature needed for the equilibrium of a given ion.
Another effect which had been previously overlooked is ionization through collisional excitation to autoionizing levels (Goldberg et al. (1965)), which reduces, for some ions, the effect of dielectronic recombination. As a consequence of the inclusion of these mechanisms in the calculations, the temperature deduced from the EM curves grows significantly and comes in agreement with the ion temperature, i. e. relation (3) changes to

$$T_e(radio) < T_e(ib) \simeq T_{ion}. \quad (5)$$

(see, e. g., Jordan (1969)).

Note that now two electron temperatures become different, which is a real difficulty.

3. More Recent Determinations: the Temperature of Coronal Holes

In the seventies there have been new determinations of electron temperature, based mainly, as in the preceding years, on UV data and on EM or DEM analyses. (The function DEM (differential emission measure) is defined as

$$DEM(T) = \frac{N_e^2}{dT/dh},$$

and the temperature entering it comes, as for the function EM, from ionization balance calculations, hence it is $T_e(ib)$.)

At the same time, with the progress of the quality of the UV and X-ray observations, it became more and more clear that the solar corona was far from homogeneous. This suggested that the differences recorded in past measurements could be due to selection effects connected with the observing methods. Hence it emerged the necessity to restrict the temperature comparison to observations made on the same kind of features. Coronal holes, the uniform, low brightness regions, away from activity centers, recently discovered, were used for this study. In the eighties a new technique for determining the electron temperature, based on the ionization state of the interplanetary plasma, was introduced; furthermore new ion temperature measurements were also made, this time with the use of emission lines in the UV, rather than in the visible.

3.1. OSO satellites and radio

The observations showed that the discrepancy of eq. (5) was true also for coronal holes, although their temperature was significantly lower than that of the quiet sun: Munro & Withbroe (1971), with UV OSO-4 data, obtain $T_e(ib) = 1.05 \times 10^6$ K in the center of an elongated hole, growing to 1.45×10^6 K in a peripherical point (for a quiet area they give $T_e(ib) = 1.66 \times 10^6$ K), while Dulk & Sheridan (1974), measured a coronal hole temperature in the radio domain sensibly lower (0.8×10^6 K). (Incidentally, this showed that the past quiet sun temperatures deduced from radio observations referred to coronal holes.)
A direct comparison was made by Chiuderi Drago et al. (1977), who used OSO-7 Fe XV intensity data in the $\lambda 284$ Å line and radio data at 169 and 408 MHz from the Nancay interferometer. These authors confirmed the discrepancy between radio and UV models of coronal holes. It must be borne in mind that the observed line intensity depends not only on the temperature of the source, but also on its density, and that also, being the result of an integration along the line of sight, it includes, for observations on the disc, the contribution of the transition region. In other words eq. (4) does not define uniquely a model $N_e(h), T_e(h)$ because another equation is needed (one normally uses electron pressure = constant). (Furthermore, the function $EM(T)$ is not well defined at the maximum temperature (coronal) end). Similarly radio models also need another equation beyond eqs. (1) and (2). This means that an agreement between radio and UV coronal temperatures can be forced by varying the density distribution, but this will result in a discrepancy somewhere else. Chiuderi Drago et al. found that, varying density and temperature distributions in the range of compatibility with the UV data, the 169 MHz brightness was always larger, by a factor from 1.3 to 2, than the observed value.

3.2. The Skylab era

With the Skylab mission (1973 - 1974) many more UV and white light data, of improved quality, were obtained on coronal features, in particular on coronal holes. With these data temperature determinations were made:

- Doschek & Feldman (1977), find no emission in the Fe X $\lambda 1463$, Fe XI $\lambda 1467$ and Fe XII $\lambda 1242$ lines, and thus conclude that $T_e < 1 \times 10^6$K. (Off limb observations with the NRL spectrograph on Skylab.)
- Mariska (1978), from the analysis of several ion lines, obtains $T_e = 1.1 \times 10^6$ K. (Off limb observations with the Harvard spectroheliograph on Skylab.)
- Raymond & Doyle (1981), using the Vernazza & Reeves (1978) atlas of UV emission lines, obtain larger values: $T_e = 1.2 \times 10^6$K for the network and $T_e = 1.4 \times 10^6$K for the cells. (Disk observations.)

The temperature of the first paper of the list is clearly $T_e(ib)$. So are the temperatures of the other papers, which come from EM or DEM analyses.

Work on the subject was made also by Rosner & Vaiana (1977), who constructed a coronal hole model based on X-ray and UV data from Skylab, and radio data from various authors. Rosner and Vaiana were able to satisfy the empirical constraints, but the radio emission at 169 MHz. A direct comparison between the radio and UV temperatures of a coronal hole, similar to the one of Chiuderi Drago et al. described above, was made by Dulk et al. (1977), adding to the Skylab data (emission lines from Mg X and O VI) radio data at the frequencies 80 MHz, 160 MHz, 1.42 GHz and 10.7 GHz (from various radiotelescopes). Both sets of data were found to be compatible with a coronal temperature of 1.26×10^6 K, but the model $N_e(h), T_e(h)$ in agreement with the radio data was considerably different from the analogous one obtained from the UV data: the intensities in the radio domain calculated with the UV model were larger (up to a factor of 10), than the observed ones. The authors point out that an excess abundance of the heavy elements in the transition region and corona could explain the discrepancy.

In conclusion, the results of OSO-4, OSO-7 and Skylab are in agreement: considering unlikely the explanation based on the abundance excess, the temperature of the coronal holes deduced from the UV observations is significantly larger than the one deduced from radio observations. Somewhat in contrast with this result is the finding of Doscheck and Feldman, quoted above, which is, in fact, an early indication that the other UV determinations were incorrect.

3.3. Period between Skylab and SOHO

3.3.1. $T_e(ib)$

The disagreement between temperature determinations with different methods in the solar corona, was not discussed much in the following years, probably because of the lack of space missions during periods of time when coronal holes at the disk center could be observed, which happens close to activity minimum. (To avoid complications caused by the curved path of the rays, the observations in the radio domain must concern structures at the disk center.) There are, however, a few determinations of $T_e(ib)$ in coronal holes during this period:

- Galvin et al. (1984) and Ipavich et al. (1986) find $T_e = 1.3 - 1.4 \times 10^6$ K with *in situ* measurements of the ionization state of the fast solar wind, assuming a freezing of this state at some height in the solar corona. Such determinations are relevant for coronal holes because, as established in the seventies, they are the sources of the fast solar wind.
- A summary of the situation is made by Withbroe (1988), who discusses previous observations and calculates coronal hole models. All of them have the maximum electron temperature above 1.4×10^6 K.
- Guhathakurta et al. (1992), from the intensity ratio of the green (Fe XIV) and red lines (Fe X), find electron temperatures in the same interval for the South polar coronal hole at the heliocentric distance $r = 1.15 r_\odot$. They use eclipse observations (continuum and green line) and ground-based coronagraph observations (green and red lines).
- Habbal et al. (1993) use three line ratios (from O VI, Mg X and Ne VII), which allows them to determine not only a relatively narrow temperature interval, but also the relative abundances of the element considered. They obtain 7.8×10^5 K $< T_e < 9.3 \times 10^5$ K, between 1.02 and 1.07 $r_\odot$. This result is quite remarkable because for the first time an UV electron temperature is small enough to be in agreement with the radio temperatures. Note that the data are from the SO-55 instrument of Skylab, as in a number of former studies. This paper contains also an interesting analysis of the previous temperature determinations.

– Hara et al. (1994), with the use of soft X-ray data from the SIX instrument on the Yohkoh satellite, find 1.8×10^6 K $< T_e < 2.4 \times 10^6$ K.

3.3.2. T_{ion}

Furthermore, in this period, the first measurements of T_{ion} in coronal holes have been accomplished. The successful launch of a slitless spectrograph in the shadow of the 1970 eclipse showed that the emission of the extended corona was dominated, in the UV, by Ly-α radiation (Speer et al. (1970)), which was shown to be due to resonance scattering, by residual neutral hydrogen atoms, of the chromospheric Ly-α emission (Gabriel et al. (1971)). This observation gave the start to the exploration in the UV domain of the extended corona (i. e. above $\sim 1.2r_\odot$), which had been observed previously only in the visible and radio spectral regions.

Measurements of the Ly-α coronal line were made, in the following, by means of a coronagraph-spectrometer on board rockets, which gave, in a polar coronal hole, $T_{ion} = 1.8 \times 10^6$ K at 2.5 $r_\odot$ in 1979 (Kohl et al. (1980)), but sensibly lower values (60%) in 1980 (Withbroe et al. (1985)). Note that these observations refer to a period of high solar activity, since the sunspot maximum was in 1979. Later on, observations from the Spartan platform found non-Gaussian Ly-α profiles in polar coronal holes, with wings corresponding to high temperatures $(4 - 6 \times 10^6$ K) (Kohl et al. (1996)).

4. SOHO

On board the SOHO satellite there are five instruments which observe the solar corona: EIT, CDS, SUMER, LASCO, UVCS.

These instruments have permitted to tackle the problem again, by a new set of measurements of both T_e and T_{ion}.

4.1. T_e

The UV data have been analyzed by constructing the EM(T_e) or DEM(T_e) curves, as in the seventies, but also by studying line intensity ratios. Note that for lines belonging to different ions of the same element, no errors connected with abundance values are involved, for lines belonging to the same ion not only abundance values, but also ionization calculations are not required. In the latter case the temperature is deduced by considering the transitions which determine the level populations, which are caused by spontaneous decays and electron collisions; thus the temperature obtained is an electron temperature, $T_e(lr)$.

These studies have essentially confirmed the result of Habbal et al., quoted above, i. e. the coronal hole temperature deduced from the UV data is now considerably smaller than that deduced in the seventies, not only using the latter method, but also the former, i. e.

$$T_e(ib) = T_e(lr) < 1 \times 10^6 K,$$

in spite of the fact that the observational data had not changed significantly. (For example the comparison of the Chiuderi Drago et al. data (see below) with those of Vernazza and Reeves (section 3.2) does not show any decreasing trend.) Here is a list of coronal hole temperature determinations based on the data of the SOHO instruments:

- Insley et al. (1997) find a very scarce emission in the Fe XIII λ320.80 and Fe XVI λ335.40 lines in the CDS observations of a coronal hole.
- David et al. (1998), with data from CDS and SUMER, find T_e growing from $\simeq 8 \times 10^5$ K at 1.05 $r_\odot$ to a value $<$ 1×10^6 K at 1.15 $r_\odot$, and then decreasing to $\simeq 4 \times 10^5$ K at 1.3 $r_\odot$. (O VI line ratio.)
- Wilhelm et al. (1998), with SUMER data, find T_e, inside plumes, in the interval 7.3×10^5 K - 7.9×10^5 K up to $\sim 1.2r_\odot$, decreasing to 5.8×10^5 K at 1.3 $r_\odot$, while outside plumes it grows from

7.8×10^5 K at 1.03 $r_\odot$to 8.8×10^5 K at 1.3 $r_\odot$. (Mg IX line ratio.)

- Fludra et al. (1999) find a quite similar result with CDS data referring to the height interval 1 - 1.2 $r_\odot$. (Ratio of lines of two different ions of the same element, Mg X and Mg IX.) These authors show also that the northern and southern polar holes were essentially equal as far as temperature and density were concerned, and that these parameters remained constant for a period of seven months.
- Chiuderi Drago et al. (1999) obtain, from UV SUMER data concerning a coronal hole (on disk observations), a DEM distribution, which they use to compute the radio brightness temperature as a function of the frequency. The computed brightness temperature is in good agreement with the observed one for frequencies larger than $\sim$ 220 MHz. At 164 MHz the calculated T_b is too low.

  This is the opposite of the situation of the seventies!

  The authors find agreement between radio and UV data also at 164 MHz adding an isothermal corona on top of the transition region. (This corona has a small influence on the UV emission of the considered ions, but has an important effect on the emission at 164 MHz.) This improved model has a coronal temperature $T_e \lesssim 9 \times 10^5$ K.
- Del Zanna & Bromage (1999), with a DEM analysis and one based on a Mg IX to Mg X line ratio, find the peak of the emission measure at $T_e = 8 \times 10^5$ K, decreasing rapidly at higher temperature, with very little material above 10^6 K. (On disk observations.)

In conclusion, after the observations of the SOHO instruments, there is a general agreement for the maximum temperature in coronal holes, i. e. :

$$T_e(ib) \simeq T_e(lr) \simeq T_e(radio)$$
$$\simeq 8 \times 10^5 K. \qquad (6)$$

4.2. T_{ion}

Important new results on T_{ion} have been obtained by UVCS, which has shown that, in coronal holes, the kinetic temperature of the ions O VI and Mg X grows with the heliocentric distance and reaches very high values ($> 2 \times 10^8$K for O VI at 2.1 $r_\odot$), while the H I temperature is much smaller and grows slowly (2.4×10^6 K at 2.1 $r_\odot$) (Kohl et al. (1997)). At lower heights the behaviour of T_{ion} has been determined by SUMER, for the ions Mg IX e Si VIII (Wilhelm et al. (1998)). The values obtained are in the interval $\sim 3 - 6 \times 10^6$ K at heliocentric distances between 1.03 and 1.3 $r_\odot$.
The velocity distributions of the ions are not only very wide, but also strongly asymmetric (with the exclusion of hydrogen) (Kohl et al. (1997)): the high ion temperatures quoted above refer, in fact, to the distributions of the line-of-sight velocity components, the radial components having a much narrower distribution (standard deviation smaller by at least a factor of 7 at 3 $r_\odot$(Kohl et al. (1997))). It must be stressed that these characteristics of the ion velocity distributions (large width and asymmetry) do not occur in streamers, but only in coronal holes.

5. Discussion

Before discussing the difference $T_{ion} - T_e$, let us consider the disagreements still existing about T_e. As we have seen, the determination of this quantity based on the ionization state of the fast solar wind gives a value considerably larger than that of eq. (6), and a new result (Ko et al. (1997)) agrees with the old one. One should probably have less confidence on these temperatures than on those of eq. (6), because the former require a density and velocity model for the coronal source of the plasma. However, it is difficult to accept an ionization state of the plasma in the interplanetary space corresponding to a temperature larger than any one encountered by that plasma during its motion. Thus the fact that the coronal electron temperatures deduced from *in situ* measurements are larger than those obtained by remote sensing (radio and UV) poses a real problem. And this is made somewhat harder by the X-ray determination quoted above (Hara et al. (1994)), although the latter, being based on images obtained with broad-band filters, is probably more subject to errors.

At any rate, after the determinations of the SOHO instruments it is clear that the difference $T_{ion} - T_e$ is real. It can not be attributed to turbulence or waves, or any kind of macroscopic motions, because in this case the velocity distributions of the various ions would be the same and thus the kinetic temperatures would be proportional to the ion masses, which does not corresponds to the observations. Hence there is a real temperature difference between ions and electrons. It is well known that the most diffuse explanation is that the energization of the ions is due to resonance between cyclotron motions about the magnetic field (which in the coronal holes is quasi-radial) and high frequency transverse waves propagating along it, a mechanism which would also explain the asymmetry of the ion velocity distributions discovered by the UVCS instrument of SOHO.

6. Conclusions

The history of the determination of the coronal temperature is like a detective story, with a couple of unexpected coups de théatre. Initially the investigators were worried by the difference $T_{ion} - T_e(ib)$, and followed this track, without giving due attention to $T_e(radio)$. As a result of the investigation, a culprit was found (neglect of dielectronic recombination), but then the difference $T_e(radio) - T_e(ib)$ begun to appear more and more the crime, and, at the same time, the difference $T_{ion} - T_e(ib)$ less and less so. When the observations showed that the solar corona was very inhomogeneous there was hope that the crime did not exist: different observing methods measured different structures. But this did not last long: measurements made on particular features (coronal holes) confirmed the difference $T_e(radio) - T_e(ib)$. In the last period of the story, the final coup de théatre: the crime has disappeared in recent times, and there is no clear responsible for its perpetration in the seventies, although, without doubt, the culprit, or culprits, are to be found among the errors in the atomic parameters used in that period for the ionization calculations. It is remarkable that no one, as far as I know, among those who made use of such parameters, suspected so, which may suggest that these people should be considered accomplices (involuntary, of course) in the crime. It could be that the last chapter of the story is still to be written, given the discrepancies still existing, pointed out in the last section. But even in this case I think that the chapters already written contain an interesting lesson.

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