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Physics of the outer atmosphere of the Sun and of stars along their evolutionary track

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Abstract. We discuss the activity of a Co-financed project dedicated to study stellar activity and, more in general, stellar properties, through observations in X-ray, UV, optical etc. bands and through modeling. A key aspect of the project is the study of activity of stars in various phases of their evolution so as to ascertain the role of evolution in determining activity and the role of activity in influencing evolution, e.g. through the significant loss of angular momentum. An even more detailed study, thanks to its proximity, of the Sun is a fundamental part of this project; the relevant information is indeed both important for solar physics 'per se' and to help defining with a high level of detail, and therefore of insight, the physical conditions in the solar atmosphere which thus is an important reference for the studies of stellar activity.

Key words. Sun: activity – Sun: atmosphere – stars: activity – stars: atmospheres – stars: evolution

1. Introduction

This project was dedicated to study solar and stellar activity and to the relevant effects of non-thermal heating in coronae, chromospheres and transition regions of late-type stars (spectral type F to M) through X–ray, UV, radio etc. observations. This is now a mature field, well within the main stream of stellar physics to which it contributes with crucial information, e.g. on the loss of stellar angular momentum with age or on the effects of different chemical abundances. Part of the project was also dedicated to optical observations to study stellar photospheres and chromospheres to put in the right context the activity studies, through accurate determination of the spectral type, of chemical abundances, of the photospheric structure, of the rotation velocity etc. Studies of the Sun were fundamental to obtain a high physical insight and a better understood reference for all the activity and evolutionary studies.

The project involved eight groups (listed below with their leaders), each with different expertises and involvements in different aspects of the project: at the University of Palermo (UNIPA, G. Peres,

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also coordinator of the whole project), at the Observatory of Palermo (OAPA, R. Pallavicini), at the Observatory of Catania (OACT, D. Spadaro), at the observatory of Naples (OANA, L. Terranegra), at the University of Florence (UNIFI, M. Landini), at the Observatory of Arcetri (OAFI, G. Poletto), at the Observatory of Turin (OATO, E. Antonucci) and at the Observatory of Trieste (OATS, C. Morossi).

Several of the groups were collaborating before this co-financed project and several other collaborations started, thanks to it; several facets of the problem stellar activity and its evolution have been tackled and solved by the collaborating teams. For ease of presentation, we group the activity in two main fields: *"Study of the Sun, modeling and development of diagnostic tools"* and *"The properties of solar–type stars and their evolution"*; almost all the groups contributed to both.

2. Study of the Sun, modeling and development of diagnostic tools

The task has been studying the outer solar atmosphere, developing models and collecting, analyzing and interpreting data. It has been equally important to bring the detailed physical knowledge of solar corona into the study of stellar coronae: the teams investigated several solar and stellar observations per se but also strived to cross-fertilize the two related fields. Such an approach is particularly evident in the study of the Sun as a star, the so called solar-stellar connection, in the X–ray band.

2.1. Energetics and dynamics of the solar and stellar plasma: data analysis and models

The OACT group investigated the dependence of the wavelength shift of the coronal emission line profiles on the line of sight velocity of the emitting plasma. To this end a set of emission profiles expected from the extended solar corona were computed.
The results of the calculations showed that the wavelength shift of the collisionally excited component of the line is related to the line of sight velocity by the usual formula for the Doppler effect; on the contrary, the wavelength shift of the resonantly scattered component also depends on the angle of scatter and on the angle between the velocity vector and the line of sight.
For the same outflow velocity, the absolute value of the resonantly scattered component shift is significantly smaller than that of the collisionally component. Since both mechanisms generally contribute to the formation of a coronal line, the results of this work should be taken into account when deducing line of sight velocities from the analysis of emission line profiles observed in the extended corona.

A work of the OACT, OAPA and UNIPA groups aimed at deriving useful diagnostics and identifying possible signatures of Alfvén waves momentum deposition in the most intense EUV spectral lines emitted by the solar plasma in the acceleration regions of the solar wind. More specifically, this work investigated, with the help of a detailed wind model (Orlando et al. 1996), the insight and the constraints that UVCS/SOHO observations give on the presence of Alfvén waves, as deduced from the influence of the waves on the solar wind structure and dynamics.
The authors synthesized the emission in the Lyα, Lyβ and O VI doublet (1032 Å, 1038 Å) lines from a computed set of wind solutions, characterized by different physical conditions, and derived possible diagnostics. They finally compared their results with the most recent UVCS/SOHO data, finding interesting indications for the spectral detection of Alfvén waves in the extended corona.

Another activity of the OACT group was the participation, as UVCS representative, in the MEDOC campaign n. 4 and 6. These are observational campaigns carried out at the Institut d'Astrophysique Spatiale, Orsay - Paris, which coordinate joint observations by several instruments

on board the SOHO spacecraft.
During the second campaign two coronal mass ejections were observed by UVCS, related to the eruptions of a large filament structure in an active region close to the West limb of the Sun, and of a prominence near the South Pole, respectively. Intensity and profile of the O VI resonance doublet lines at 1032 Å and 1038 Å and of Lyβ (1026 Å) line, together with the intensity of some other minor ions, were observed using the O VI channel of UVCS. Catania researchers analysed these spectroscopic observations in order to get information about the distributions of ionic densities and flow velocities in the solar coronal plasma ejected during these transient events. Emission in ions ranging from C II to O VI indicates a temperature range between $10^{4.5}$ and $10^{5.5}$ K. The morphology of the bright emission regions suggests the development of several strands of plasma irregularly distributed inside the CME structures, whose temporal evolution is significantly different from each other. The velocities determined for each bright element also provide a complex picture of the plasma kinematics characterizing these coronal mass ejections.

X–ray and UV observations, along with accurate models have been used to study coronal plasma, in the course of different events, always paying attention to a careful and detailed comparison data-models. We studied syphon flows in coronal arches, and their UV emission, including non-ionization equilibrium. Using the fluid-dynamics Palermo-Harvard model and XUV observations, at high time and space resolution collected with the TRACE orbiting telescope, of a turning-on coronal loop, has allowed the OAPA group to derive the spatial distribution and evolution of the transient heating responsible of the event (Reale et al 2000a,b). Modeling the emission of a bundle of independent plasma filaments forming a coronal loop, it was shown that TRACE tendentially sees such structures as isothermal (Reale & Peres 2000).

By jointly using images at high angular resolution collected in XUV with NIXT and in X–ray with Yohkoh we were able to find the evolution of the filling factor of the coronal plasma during the long-term evolution of a set of coronal structures (Di Matteo et al. 1999).

OAPA and UNIPA also studied the effects of non-equilibrium ionization on Yohkoh/SXT temperature and emission measure determination during flares and microflares (Orlando et al. 1999).

OAFI undertook the task of developing a model of solar wind which does not require ad hoc functions either to explain the wind acceleration mechanisms or the momentum and energy deposition laws. The model was based on a two-fluids treatment and the treatment of the helium component was an approximate one. Model prediction have been compared with data, collected 'in situ' with Ulysses and, with observations of the low corona made with SOHO, showing good agreement. The model has been compared with other models which hypothesize the acceleration of the solar wind through the dissipation of Alfvén waves through the ion-cyclotron resonance and they have pointed to the observations needed to identify the mechanism at work. The work has also tried to identify the area on the Sun from which the wind originate, checking that it indeed is the originating area of the wind and not of sporadic fast 'jets', certainly easier to identify but not very important as far as their mass contribution to the wind is concerned.

2.2. Spectral diagnostic tools

The development of the CHIANTI code and the related diagnostics has been the work of the team at UNIFI. The main activity has been the upgrade of the CHIANTI database, very rich of atomic data crucial for the diagnostics of optically thin plasmas (Landi et al. 1999; Landi & Landini 1999; see also Fig. 1). At the end of this project it included the atomic models available in literature up to the en-

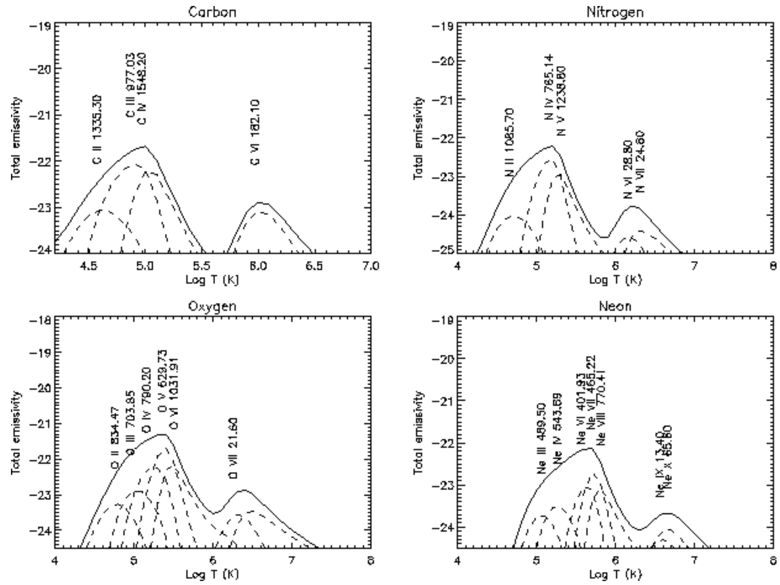

Fig. 1. An example of the contribution functions of the strongest line of each ion to the total emissivity of the most abundant elements (from Landi & Landini 1999).

ergy level n=3 of virtually all the ions of the most abundant elements and, therefore, it represents an accurate reference for the identification of most lines observed in X–ray and UV astrophysical spectra. The database provides the atomic levels energies both from theory and from observations, when an accurate reference to them is available, the collisional cross sections, the probability of spontaneous transitions, etc. Auxiliary programs allow us to calculate the population of all the levels in statistical equilibrium, vs. temperature and electron density. Also, specific tables provide the ionization equilibrium according to the most used models and to different choices of chemical abundances, so as to determine the emitted power in each line from an optically thin plasma. Auxiliary programs allow the user to compute the emission in the continuum by free-free, free-bound e 2-photons processes in bands and at temperatures within the range 10^4 K e 10^8 K, selected at will.

CHIANTI database now makes up a large fraction of Atomic Plasma Emission Database (APED) developed at the Center for Astrophysics, Cambridge (USA), (the main database of this kind used at CfA and MIT) also for the analysis of data collected with the Chandra satellite.

The database is widely used in the solar community to analyze and interpret X–ray data as well as the UV spectral data collected with SOHO/CDS and SOHO/SUMER. It is also publically available at the three institutes collaborating to the project: Arcetri[1] (Florence) and at NRL (Washington) and DAMTP (Cambridge, UK).

Papers produced within the development of diagnostics with CHIANTI have used the database with the following main results:

– for the first time it has been proved the compatibility of radio measurements of the quiet coronal emission with X–ray and UV line measurements, a com-

[1] `http://www.arcetri.astro.it/science/chianti/chianti.html`

patibility challenged in many previous works;

- while testing and comparing different models of ionization equilibrium, it has been shown that different ionization models may lead to rather different values of chemical abundances (up to a factor 2) and they may change from a place to another in the solar atmosphere; this result is very important in the context of the effect of the First Ionization Potential (FIP Effect) in determining the local abundance of the specific element.

Also OATO had the main task of developing diagnostic methods to interpret the UV emission from the outer regions of the solar corona. They developed a model of the Doppler dimming of the hydrogen Lyα 1216 Å, describing the decrease of the line intensity vs. the speed of the solar wind and vs. height. The Doppler dimming curve, vs. radial distance, has been computed according to a model of spherically symmetric atmosphere, considering either an isotropic distribution of neutral hydrogen atoms or possible anisotropy perpendicularly to magnetic field. The diagnostics of Doppler dimming of hydrogen Lyα has then been applied to UV observations, to derive the H atoms speed, in the course of coronal expansion. Equally, they have fully developed the model of the line intensity of O VI 1032 Å e 1037 Å, taking into account both the pumping of the line O VI 1037 due to the nearby lines C II 1036.34 Å and 1037.02 Å, and the anisotropy of the distribution of oxygen ions velocity. This diagnostics has been applied to coronal data collected from space, in order to derive the solar wind speed in coronal holes and the results have been published; see Fig. 2 (Giordano et al. 2000a,b; Antonucci et al. 2000). The data analysis based on the method developed by OATO has allowed also to establish in detail the regions within the coronal holes from which the wind originates; the fast solar wind appears to be preferentially accelerated in the regions outside polar plumes. The Doppler dimming curves have also been computed for the lines Si XII 499 Å and 521 Å using coronal models analogous to the preceding ones. The application of Si XII lined Doppler dimming as a diagnostic tool is, however, difficult.

2.3. Radio monitoring and studies of impulsive events

OATS analysed the impulsive solar radio events to study the acceleration processes occurring in the solar corona. An entire series of radio events was analyzed to demonstrate the existence of acceleration processes on an extended spatial scale in the solar corona. Special attention was given to the nonlinear analysis of time series relevant to the observation of radio phenomena that can provide a parametric description of the various observed components in the attempt to extract physical information on the underlying physical system and its nature, most of which exhibited nonlinearity and nondeterminism (Veronig et al. 2000). A diagnostic was set up to derive the coronal magnetic field based on the time delay in the propagation of the two magnetoionic modes, observed as the two circular polarization components of the electromagnetic emission, according to the inferred topology and magnetoionic character of the plasma layers perturbed by the propagating electron beam (Ledenev & Messerotti 1999). Analytical expressions were derived to represent the coronal magnetic field in axisymmetric geometry and under the potential field hypothesis to have a flexible modeling tool in coronal radio events modeling. In this framework, the installation of an imaging magnetograph at the Solar Observatory Kanzelhoehe (Austria) and its development allowed us to start simultaneous observations of active regions in the optical and radio bands aimed at improving the comparative study and modeling (Warmuth et al. 2000). Similarly the coincidence was studied between magnetic oscillations and Hα bright points as well as

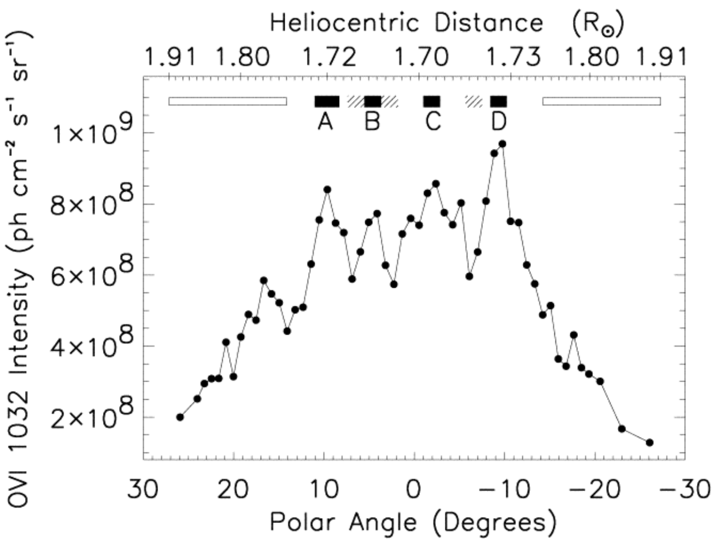

Fig. 2. Transversal structure of the inner corona in the polar coronal hole, showing the presence of the several plumes, as imaged in the emission of O VI 1032 Å line, observed with UVCS/SOHO (from Giordano et al. 2000).

the coronal magnetic structures associated with long-lasting type IV radio events and impulsive events with fine structures.

2.4. Sun as an X–ray star

Studying the Sun as an X–ray star, i.e. the solar-stellar connection in the X–ray band and its implication on both stellar and solar physics led us to several fundamental works. They first concentrate on defining and tuning the method to use the solar X–ray data collected with Yohkoh/SXT and to derive the emission measure distribution vs. temperature for the whole solar-corona (Orlando et al. 2000). They also allow us to determine, using such a distribution, along with the spectral synthesis codes, the solar corona emission in each X–ray and XUV band of interest and to simulate observations of an identical star made with a stellar observatory such as ROSAT (Peres et al. 2000; see Fig. 3) or Chandra and XMM.

These works paved the path to the direct comparison of solar observations with stellar ones; furthermore they opened a new perspective on the use of the solar data themselves. A few follow up works include the study of flares as a class of phenomena (Reale et al. 2001), and of the contribution of the various kinds of structures to the emission of the corona on the Sun and on other stars (Orlando et al. 2001).

In the context of this project the study of the Sun as an X–ray star has been the bridge between the solar and the stellar physics.

3. The properties of solar–type stars and their evolution

In the present section we will focus on the stellar part of the project in which researchers from Arcetri, Napoli, Palermo, and Trieste were involved. With the primary goal of putting the Sun in perspective, four main issues were investigated; namely:

– evolution of coronal activity in solar–type (and lower mass) stars;
– Li abundances and mixing processes among open cluster stars;

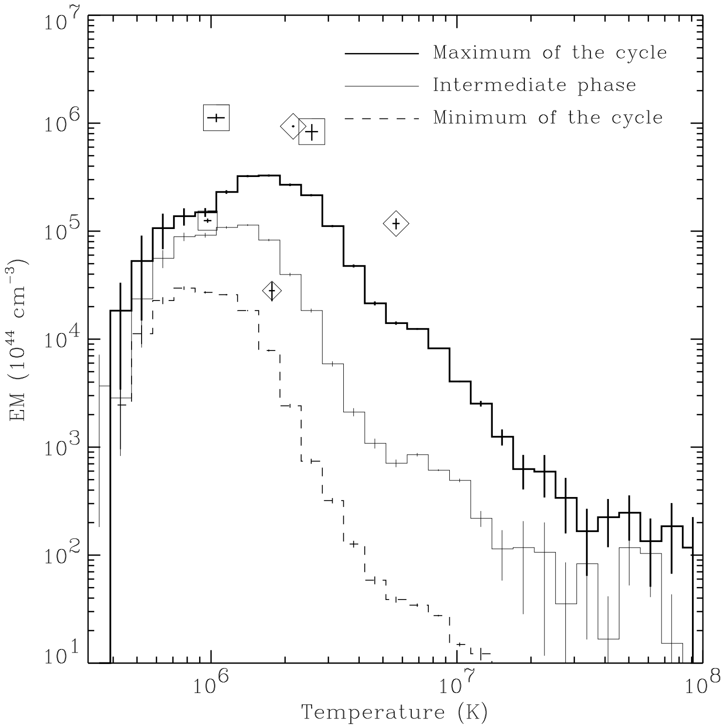

Fig. 3. Emission measure distribution vs. temperature of the solar corona at maximum, low and intermediate phases of the solar cycle We also show the results of the spectral fitting of the synthesized spectra folded through the ROSAT/PSPC and ASCA/SIS spectral response; squares: fitting of ROSAT/PSPC spectra, diamonds: fitting of ASCA/SIS spectra, large symbols: Sun at maximum of the cycle, small symbols: Sun at minimum (from Peres et al. 2000).

– the characterization of the evolution of solar-type stars from the pre-main sequence (PMS) to the zero age main sequence (ZAMS);
– the photospheric structure of solar–type stars.

The research activity was based on several observing campaigns at a variety optical and X–ray facilities, such as the ROSAT satellite, IUE, the ESO 3.6-m telescope in conjunction with CASPEC, the Loiano telescope, and the telescopes at San Pedro Martir and the Haro Observatory in Mexico. In the following sections we will describe the major results of the research activity.

3.1. X–ray emission and coronal activity

X–ray surveys of open clusters allow us to follow the evolution of a solar-like corona from the very early times on the main sequence (MS) up to the solar age (and, in principle, even to older ages). At the same time, surveys of clusters provide a fundamental tool to determine the relationship between coronal properties and other stellar parameters, such as rotation and mass and to investigate whether and to which extent the evolution of activity of solar–type stars is unique.

Within the present project, the teams at OAFI and OAPA have carried out ROSAT observations of variety of open

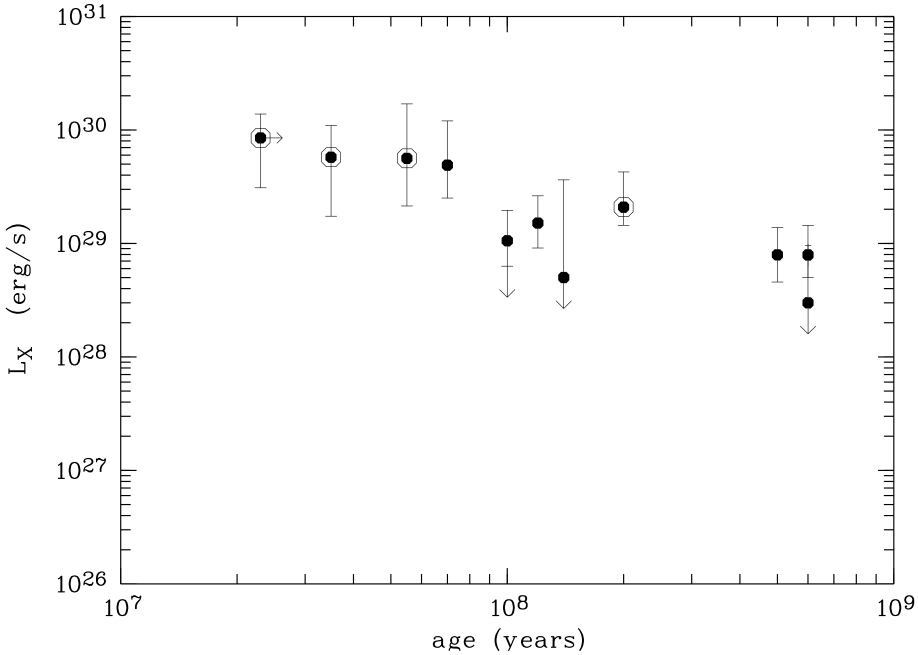

Fig. 4. Median X–ray luminosity as a function of age for solar–type stars in different clusters. The vertical lines connect the median with the 25th and 75th percentiles. Circled symbols denote X–ray selected cluster samples.

clusters (Franciosini et al. 2000a,b; Micela et al. 2000; Sciortino et al. 2000). The observations and the comparison with data for other clusters, previously obtained by us or by other groups, have allowed us to define a detailed empirical scenario and to put further constraints on the age-rotation-activity (ARAP) paradigm for solar–type stars (Randich 2000). At a fixed mass, the X–ray luminosity of a star is mainly determined by its rotational velocity, increasing with increasing rotation up to a saturation threshold. The X–ray distribution function (XLDF) of a given cluster with a given age is thus mainly determined by the rotation distribution. Since, as well known, stars spin down during their permanence on the MS, the average X–ray luminosity is expected to decay. Observations of clusters clearly indicate that the average X–ray luminosity does indeed decrease with stellar age, but the decay cannot be simply described as a power law (e.g. $L_X \propto t^{-0.5}$). The results are summarized in Fig. 4 (adapted from Randich 2000), where the median X–ray luminosity is plotted vs. stellar age. The figure shows that first, at each age a large dispersion in luminosity is present, as indicated by the 25th and 75th percentiles; second, clusters younger than α Per (70 Myr) have very similar median luminosities, while a large decay takes place between 70 and 120 Myr; third, clusters of similar ages do not have necessarily the same median luminosity (and the same XLDF). The most well known case is that of the Hyades and Praesepe: the two clusters are coeval, but show different X–ray properties (Randich & Schmitt 1995), with Praesepe being significantly less luminous than the Hyades. Other cases of X–ray underluminous clusters have been found within our project, such as NGC 3532 (Franciosini et

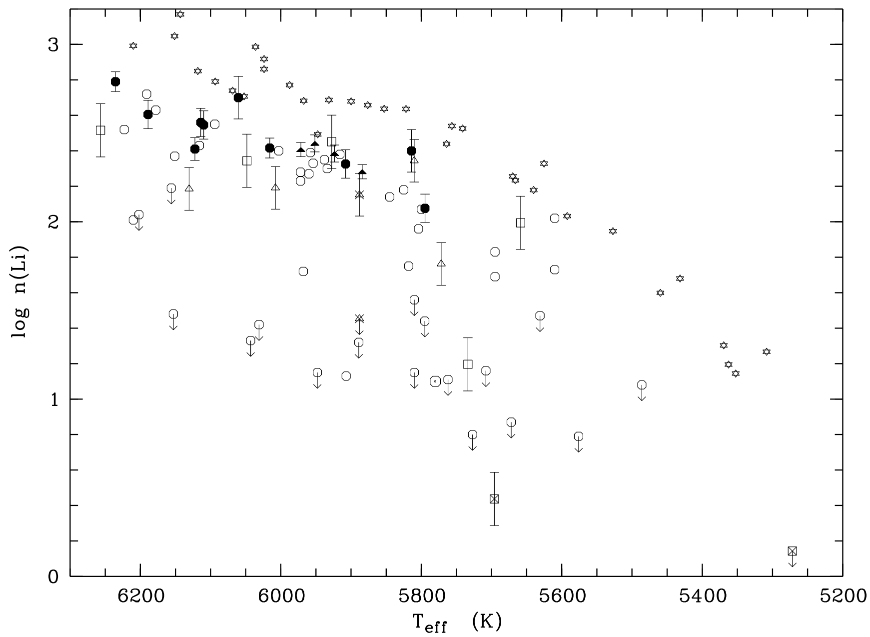

Fig. 5. Lithium abundance (in the usual scale where log n(Li)= log (n(Li)/n(H)) +12) as a function of effective temperature for IC 4651 (filled circles −2 Gyr), NGC 3680 (filled triangles −2 Gyr), the Hyades (stars −600 Myr), and M 67 (open circles −4.5 Gyr).

al. 2000a) or Stock 2 (Sciortino et al. 2000). Additional optical and X–ray observations of these clusters are needed, since the results may be due, at least in part, to the incompleteness of the optical membership lists and/or to not deep enough sensitivities of ROSAT data. However, if confirmed, these findings would support the hypothesis that the activity-rotation relation is not unique and that other parameters besides rotation very likely affect the level of X–ray emission.

3.2. Li abundances in intermediate age clusters

The study of the evolution of the chemical composition of stars caused by nuclear reactions and/or internal mixing mechanisms is one of the basic ingredients of stellar evolution studies. Li in particular is especially interesting since, due to the relatively low temperature at which it burns, it traces mixing mechanisms in stellar interiors. Observations of Li among open cluster stars have evidenced discrepancies between 'standard' models predictions (based on convective mixing only) and the observational scenario (e.g., Jeffries 2000; Pasquini 2000 and references therein). For instance, standard models predict that solar–type stars should not deplete Li after arrival on the ZAMS, while the comparison of clusters of different ages clearly show that they do destroy Li on the MS. The solar Li abundance, a factor of ∼ 100 below the initial abundance, is a long-standing still unsolved problem. In addition, the tight Li vs. temperature relationship observed in the 600 Myr old Hyades is not mimicked by the behavior of similar solar–type stars in the solar age cluster M67, where a large dispersion (a factor of 10, at least) in Li abundance has been found. These results in-

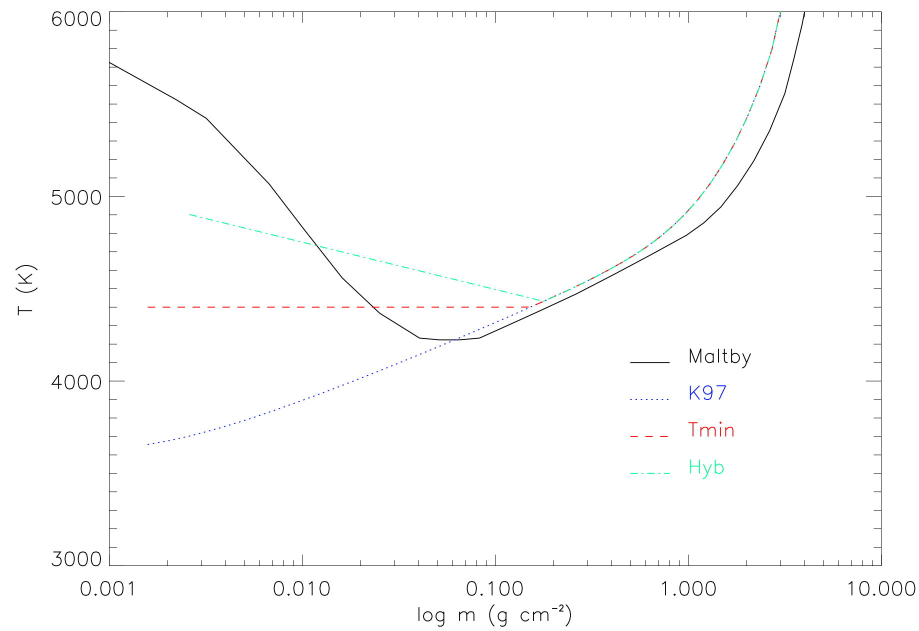

Fig. 6. Temperature structures of atmosphere models of solar–type stars. Tmin and Hyb represent our semi-empirical models, and Maltby et al. (1986, Maltby) and Kurucz (1997, K97) refer to standard solar models.

dicate that non-standard mechanisms processes, such as rotational mixing, diffusion, mass loss, or gravity waves must be taken into account.

In order to empirically constrain proposed mixing processes, the groups at OAFI and OAPA carried out Li observations of the two $\sim$ 2 Gyr old clusters IC 4651 and NGC 3680 (Randich et al. 2000; Pasquini et al. 2001). In Fig. 5 the Li vs. effective temperature distributions of the two clusters is compared to the Hyades and to M 67. The Sun is also included in the figure. The figure shows that the 2 Gyr clusters have very similar Li vs. $T_{\rm eff}$ distributions, which lie slightly below the Hyades distribution. Neither cluster is characterized by the dispersion in Li which is observed in M 67, suggesting that either the dispersion develops after $\sim$ 2 Gyr or that different initial conditions lead to different evolution of Li abundances. In addition, stars in the upper envelope of the M 67 distribution have the same Li content as stars in the 2 Gyr clusters; the finding may imply that these stars have not suffered any significant depletion between $\sim$ 2 and 4.5 Gyr or that they had a much slower overall Li depletion, due for example to a different chemical composition. We finally mention that none of the existing models appears to reproduce the observed features.

3.3. Evolution of solar–type stars from PMS to ZAMS phase: cbservations and modeling

The OANA team focused on two different, but related aspects; namely,

a) The study of the correlation between the stellar structure and the angular momentum loss during early evolutionary stages of a solar–type star with a circumstellar disk;

b) the study of the evolution of chromospheric activity indicators of solar–type stars from the PMS to ZAMS phases and their correlation with the stellar parameters.

Point (a) was addressed by computing the Hα synthetic line profiles for the star FU Orionis and by comparing them with high spectral and time resolution observed spectra. Radiative transfer and kinetic equilibrium solution were achieved by MULTI code in non-local thermal equilibrium. We were able, in plane parallel geometry, to explain the red edge of Hα emission as due to the effect of a chromospheric gradient at the base of the wind (i.e. between the disk and the wind). The Hα red semi-profile results to be a good diagnostic of structure temperature; the blue semi-profile instead traces the wind acceleration, with a high sensitivity to the gradient of velocity in the inner wind. Different atmospheric models were constructed to match observed line profiles with strong implications of theoretical interpretations of these objects (D' Angelo et al. 2000).

In order to address point (b) we obtained spectra in the Ca II infrared triplet (CaIRT) region and $ubvy-\beta$ photometry of a number of solar–type PMS stars (classical and weak-line T Tauri stars, CTTS and WTTS) in different star forming regions (SFR – Taurus-Auriga, Orion, Serpens, Scorpio) and of cool stars both in field and in young open clusters (α Per and the Pleiades). Photometry allowed us to derive effective temperatures, gravities, luminosity and distances for the target stars and to start the study of their correlation with chromospheric activity indicators such as the CaIRT. Our preliminary analysis shows that CaIRT is a good activity diagnostic for PMS stars. Indeed the WTTS occupy a peculiar position in the EW (CaIRT) versus $\log T_{\rm eff}$ and EW(CaIRT) versus $\log \mathrm{L_X/L_{bol}}$ (the ratio of X–ray to bolometric luminosity) diagrams with respect to older field and cluster stars. More specifically, WTTS show a lower intensity of the CaIRT equivalent width than active solar–type ZAMS stars, due to an emission (chromospheric) component in the CaIRT absorption line (Alcalà et al. 1998; Chavarria et al. 2000; Terranegra & Chavarria 2000; Terranegra et al. 2000).

3.4. Photospheric structure of solar–type stars

The team at OATS analyzed a set of UV spectra (from the IUE INES archive) combined with visual ones (new observations taken at the G. Haro Observatory, Cananea, Mexico) in order to derive detailed information on the photospheric structure of solar like stars (Franchini et al. 1998; Morossi et al. 1998, 1999a, 1999b, 2001). Particular attention was devoted to the modeling of the *temperature minimum region* in the upper photosphere of G–type stars. The flux distributions obtained from new semi-empirical models characterized by different atmosphere structures were compared with predictions from the solar (Maltby et al. 1986) and Kurucz (1997, private communication, CD-ROM in preparation) models. The different temperature structures are summarized in Fig. 6.

Acknowledgements. The results here mentioned are only a short synthesis of the vast amount of work produced by a large team. More details, along with the complete bibliography can be obtained from the authors or, in part, from the relevant site at CINECA. It is worth mentioning, in any case the important role played by the local coordinators: R. Pallavicini, D. Spadaro, L. Terranegra, M. Landini, G. Poletto, E. Antonucci, C. Morossi (with help from M. Messerotti). It is just appropriate to thank the Ministero dell'Università e Ricerca Scientifica for funding this project through the COFIN/PRIN.

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