F stars: A challenge to stellar evolution

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ABSTRACT

Many main-sequence F and early G stars are too luminous for their effective temperature, surface gravity, and chemical composition. These overluminous stars have two curious properties. First, their kinematics as a function of age from stellar evolution modeling (isochrone fitting) is very different from that of normal stars. Second, while X-ray luminosity of normal stars declines with age, the X-ray luminosity of overluminous F stars changes in the opposite direction, being on average higher for older stars. These properties imply that, in defiance of standard models of stellar evolution, F stars of a given mass and chemical composition can evolve very differently. Assuming that the models correctly describe normal stars, for overluminous F stars they predict too young age and the X-ray emission evolving in the direction opposite to the actually observed trend. This discrepancy between modeling results and observational data suggests that standard stellar evolution models and models of stellar activity are missing some important factors, which makes stellar age and predictions for stellar activity from these models problematic. The data and literature analysis presented in this paper point to a nonuniform rotation of the stellar interior as a plausible key factor able to reconcile the divergent trends in age-velocity relationships of normal and overluminous F stars and explain in a coherent and self-consistent way the overluminosity phenomenon.

Subject headings: binaries: general — stars: activity — stars: evolution — stars: kinematics — stars: pre-main sequence — X-rays: stars

1. Introduction

Solar-type stars in the mass range of ∼ 1.0 to 1.5 $M_\odot$, which are mostly of the spectral type F, are uniquely suited for examining issues of stellar evolution, evolution of stellar activity, and the history of star formation in the solar neighborhood. Their particular suitability is due to the large spread in their evolutionary status and the availability of large amounts of varied, pertinent data, as summarized below:

- F stars are the most numerous type in the Hipparcos catalog, greatly outnumbering all other types of stars with measured trigonometric parallaxes.
- For well over ten thousand F stars, uvby photometric parameters are available, which yield star’s surface gravity along with temperature, luminosity, and metal abundance.
- Thousands of these stars have measured radial velocities, which in combination with proper motion and parallax from Hipparcos yield spatial velocities.
- Over two thousand of the same population have Rosat data, which translate to X-ray luminosities when combined with Hipparcos parallaxes.
- Single F stars are well differentiated from binary stars.
- F stars on and above the zero-age main sequence (ZAMS) straddle the entire age range of stars in the Galactic disk. With known distances and photometry, this means the
availability of their age—from standard stellar evolution modeling—in the range of 0 to \(\sim 10\) Gyr.

The abundance of data from Hipparcos (ESA 1997), Rosat (Voges et al. 1999, 2000) and uvby photometry (Hauck & Mermillod 1998), with derived parameters such as temperature and metallicity and computed parameters such as age, provides a tremendously rich background to explore the evolution of stars and stellar activity of solar-type stars over a period stretching from the present epoch back to the time when the first stars were formed in the nearby Galactic disk. Earlier, we used the indicated data to address some aspects of these issues (Suchkov & McMaster 1999, Suchkov 2000, 2001, Griffin & Suchkov 2003), i.e., overluminous star is more massive than a normal one. More recently Holmberg, Nordstrom, & Andersen (2009) published refined Hipparcos parallaxes along with new data and derived parameters for many Hipparcos stars. These newly measured parameters were radial velocity and multiplicity (differentiation between single, binary, etc. stars). The derived parameters included temperature, metallicity, spatial (3D) velocity, and age. In this paper, we take advantage of that body of data to revisit and expand on our previous work.

2. Data

The base sample used in this paper is built from a set of 11900 F stars described in Suchkov & McMaster (1999). The astrometry and stellar parameters are taken from Holmberg et al. (2009). Along with the parameter constraints used in Suchkov & McMaster (1999), the current sample is additionally constrained specifically with respect to the parameters from Holmberg et al. (2009):

- Parallax error: \(\sigma_\pi/\pi < 0.15\).
- Distance: \(d < 150\) pc.
- Spatial velocity: \(v < 200\) km s\(^{-1}\).
- Metallicity: \(-1.0 < [\text{Fe}/\text{H}] < 0.5\).
- Multiplicity: no binary or triple stars; also no open cluster members.

The overluminosity parameter discussed below is constrained by \(-0.15 \leq \Delta M_{c_0} \leq 1.0\). The subsample of X-ray emitters has X-ray luminosity from Suchkov, Makarov, & Voges (2003) and is limited to \(26 < \log L_x < 33\).

3. Overluminosity

Suchkov & McMaster (1999) introduced an overluminosity parameter defined as the difference between absolute magnitude \(M_{c_0}\) derived from the uvby photometry and absolute magnitude \(M_V\) based on Hipparcos parallax:

\[
\Delta M_{c_0} = M_{c_0} - M_V. \quad (1)
\]

For F stars, the uvby parameter \(c_0\) is, in fact, sensitive to surface gravity rather than luminosity. It is a usable measure of luminosity as long as there is a one-to-one relationship between surface gravity and luminosity. The reasonably tight relationship between \(c_0\) and \(M_V\) found for well-studied nearby single F stars implies that for many stars this is indeed so. But in general, such a relationship cannot be presumed, and \(\Delta M_{c_0}\) differentiates single F stars according to their luminosity at a given surface gravity, effective temperature, and chemical composition.

By definition, single stars of normal luminosity will have \(\Delta M_{c_0} = 0\). Given the uncertainty in the measured values of the overluminosity parameter, the actual operational criterion of normal stars was set to \(\Delta M_{c_0} = 0 \pm 0.15\), which will also be adopted in this paper. Overluminous stars (the term introduced by Griffin & Suchkov 2003), i.e., stars whose luminosity is higher than that of normal stars of the same temperature, gravity, and chemical composition, are then defined as those with \(\Delta M_{c_0} > 0.15\). At a given luminosity and temperature an overluminous star has a larger surface gravity; hence, of the two stars located at the same point in the \(\log T_e - \log L\) diagram an overluminous star is more massive than a normal one.

Overluminosity distribution is continuous, peaking at \(\Delta M_{c_0} \approx 0\) and extending up to \(\Delta M_{c_0} \sim 1.5\) (see Figure 1 in Suchkov 2001). The splitting of F stars into two groups, normal and overluminous, is just a convenient way to present the issues associated with the overluminosity phenomenon rather than a division into two distinct, separate populations. As argued below, overluminosity re-
fects peculiarities in stellar evolution of stars intrinsically different from normally evolving stars. In the course of stellar evolution, the $\Delta M_{\text{c0}}$ of stars that become overluminous progressively increases at a rate that depends on the original difference between these stars and normally evolving stars, so at any given value of $\Delta M_{\text{c0}}$ there is a mixture of stars of all ages. The way we split our sample into two groups ensures that a substantial fraction of the overluminous group consists of far evolved stars. This explains why the overluminous group looks so different from the normal group in the $\log T_e - M_V$ diagram (Figure 1).

Fig. 1.— $\log T_e - M_V$ diagram for normal and overluminous F stars. The number of stars is shown in the upper right corner. A set of isochrones (labeled by age in Gyr), based on Chaboyer at al. 1999 for composition $Y = 0.27$ and $Z = 2 \times 10^{-2}$, and a line one magnitude above the ZAMS are shown for reference. Overluminous stars tend to avoid the area near the ZAMS and are on average brighter than normal stars at the same temperature.

Originally, overluminous stars that were listed as single in the Hipparcos catalog were believed to be mostly unidentified binary stars with comparably bright normal components (Suchkov & McMaster 1999). An unresolved binary with equally bright normal components would look overluminous by $\Delta M_{\text{c0}} = 0.75$. The lingering problem was that there were stars with $\Delta M_{\text{c0}}$ significantly larger than 0.75, which definitely did not fit to the binary star hypothesis. Another puzzle was that overluminous stars as a group turned out to be much older than the known binaries in the Hipparcos (Suchkov 2000). So the binaries were not the complete answer, and something else must be at work. Indeed, later we found that overluminous stars were comprised of at least three different subgroups (Griffin & Suchkov 2003). Of those three one subgroup were binaries not identified in the Hipparcos and the other subgroup were young pre-main-sequence stars. The third group was comprised of truly single main-sequence stars. The stars in this last category are the main focus of this paper.

4. Overluminosity: Age–velocity relation

Older stars are long known to have on average higher velocities, which is demonstrated by the age–velocity relation (AVR) of F stars shown in Figure 2. The effect is usually attributed to some kind of a dynamic process that gradually increases stellar velocities as time goes on. Thanks to this clear-cut relationship between age and stellar velocities, the kinematics parameters such as velocity dispersion and the mean of absolute velocities are commonly used as age markers of stellar populations. If calibrated against actual (absolute) physical age (for instance, age based on stellar evolution models), the resulting "kinematics" age can be used as a substitute for the actual age of physical groups of stars, which proves especially useful when direct age determination (more accurately, age from stellar evolution modeling) is difficult or impossible.

The age parameter in Figure 2 is taken from Holmberg, Nordstrom, & Andersen 2009. It is based on “standard” stellar evolution modeling that requires initial conditions for only three parameters: stellar mass, $M$, helium content, $Y$, and heavy element abundance, $Z$. Standard models
provide star’s luminosity and temperature as functions of age, thus allowing one to compute age from observationally derived luminosity, temperature, and chemical composition. This ”standard” age is commonly used in isochrone fitting technique to determine age of star clusters or individual stars from effective temperature, $T_e$, luminosity, $L$, and chemical composition parameters $Z$ and $Y$, so we will also be referring to it as isochrone age.

Depending on how adequate the underlying model is and how accurate the derived stellar parameters are, standard age may differ from the actual age of a star. Therefore, if a body of observational data reveals a discrepancy between the standard age and actual age, that would mean that basic premises of the standard stellar evolution models need to be reconsidered.

5. Age and kinematics

With kinematics depending only on actual (absolute) age, the AVR of any group of stars must be a unique function of standard age if the latter adequately represents the actual age. But what if a derived AVR turns out to be a non-unique function? What if groups of stars differentiated according to some property have very different AVR? The most obvious answer would be that stellar evolution modeling uses invalid assumptions, missing some underlying physics and/or some param-
eter(s) that are as important as stellar mass and chemical composition. Stars differing in such unaccounted for parameter(s) would produce different isochrone-based AVRs as their standard age does not represent actual age.

A careful examination of available data demonstrates that F stars do indeed reveal a property suggesting that there is some physical factor missing from the current standard evolution models, which affects stellar evolution in a major way. The problem can be seen in Figure 2 that shows age-velocity relation separately for normal and overluminous stars. Instead of being identical, and duplicating the AVRs in Figure 2, the AVRs for these two subsets turn out to be quite different. The overluminous stars have much higher velocities at the same isochrone age, the discrepancy increasing with age. This means that the actual age of overluminous stars is significantly underestimated with respect to normal stars. For instance, the kinematics in Figure 3 suggests that, at isochrone age of 5 Gyr, overluminous stars are in fact $\sim 2.5$ Gyr older than normal stars, i.e., older by about 50%. This inference agrees with our results obtained earlier from our original data set (Suchkov & McMaster 1999). It is to be noted that the lower panel in Figure 3 is virtually identical to Figure 7 in Suchkov (2001) even though, unlike Figure 3, the data in the latter Figure are based on the original Hipparcos parallaxes.

6. Overluminosity: X-ray – velocity relation

Stellar X-ray emission of late-type stars is a manifestation of stellar coronal activity that is associated with the star’s outer convection zone. The convection zone is thinner in stars of larger mass, disappearing in stars earlier than spectral type F. This accounts for a stronger coronal activity of low-mass stars in comparison with more massive stars of the same age. Outer convection apparently disappears altogether in stars earlier than $\sim$F5, which is argued to be the reason for the drop of coronal activity in this spectral range (e.g., Stauffer et al. 1994).

Stellar X-ray emission is commonly believed to decline with age as coronal activity decays. The decrease of X-ray luminosity of main-sequence stars with age was inferred back in the 1980’s from the Einstein surveys of open clusters and field stars (e.g., Micela et al. 1988). For main-sequence stars, coronal activity is associated with magnetic fields generated in the star’s outer convection zone. Presumably, the field generation mechanism (magnetic dynamo) is supported by the combined effect of convection and rotation. As the star ages, rotation slows down and the dynamo gets less efficient, which reduces the star’s coronal activity and drives its X-ray emission down.

![Fig. 4.— X-ray luminosity of normal F stars (diamonds) slightly declines with increasing velocities, hence with age. In sharp contrast, for overluminous stars (circles), X-ray luminosity trends up rather than down, contrary to the conventional picture of the stellar activity evolution.](image)

Figure 4 shows the relationship between spatial velocity and X-ray luminosity of normal and overluminous F stars. Intriguingly, while the behavior of normal stars in this diagram is consistent with the concept of decaying coronal activity, the behavior of the overluminous stars does not. Overluminous stars are consistently and significantly more luminous at higher velocities than at low velocities, which implies that coronal activity of these stars increases rather than decreases with age. The same conclusion was reached in our earlier study (Suchkov, Makarov, & Voges 2003).

7. Discussion

What makes a solar-mass star live longer than the current standard models of stellar evolution predict? What can make it get more active as it
ages? What do the standard stellar evolution and stellar activity modeling miss? It appears that the only important initial characteristic not included in standard modeling, a characteristic that differentiates stars of the same mass and chemical composition at the start of their evolution, is differential rotation of the stellar interior. Differential rotation of the inner of a star can cause radial mixing of the stellar material, transporting fresh hydrogen fuel into the hydrogen-burning core and thus extending the star’s main-sequence lifetime. Stars with initially different rotational velocities and velocity radial profiles would experience different amount of hydrogen enrichment, so their main-sequence lifetimes would be different.

Over the last decade, the probing of internal rotation of stars has become a major activity in the rapidly developing field of asteroseismology. As a result, a significant radial variation of rotation in the stellar interior, from the star’s fast rotating core out to the much slower rotating upper layers, appears now to be a rather well established feature that is typical for many stars. The respective studies are driven to a great degree by the efforts to solve the remaining problems in stellar evolution. For instance, Pamyatnykh, Handler, and Dziembowski (2004) addressed the problem of the angular momentum evolution and element mixing in convectively stable layers. Using asteroseismology data for υ Eri, they inferred that rotation in the star’s μ-gradient zone is three times faster than in the envelope. With this kind of velocity gradient one may expect a massive amount of rotationally induced element mixing in the inner layers of this star.

Stellar evolution modeling that includes internal rotation as a new factor additional to mass and chemical composition is becoming a popular field in stellar evolution theory. Eggenberger, Maeder, and Meynet (2010) studied the effects of rotational mixing on the properties of solar-type stars. They concluded that "Rotational mixing has indeed a large impact on the properties of the central layers by bringing fresh hydrogen fuel to the central stellar core" and "Due to rotational mixing, the main-sequence lifetime is then larger for stellar models including rotation" (see also Eggenberger et al. 2010). Ekström et al. (2012) found a considerable increase in the main-sequence lifetimes for stellar masses between about 1 $M_\odot$ and 2 $M_\odot$, by about 25%, once rotation is included. The new stellar evolution modeling, therefore, leaves little doubt that internal rotation does indeed prolong main-sequence lifetimes. It seems safe to assume that further progress in development of models featuring rotational mixing will fully explain large differences between the lifetimes of normal and overluminous stars discussed in this paper.

Stars’ differential rotation is quite likely responsible not only for longer lifetimes but also for stronger X-ray emission of overluminous stars. One may speculate that angular momentum transfer from the rapidly rotating core and inner layers of a star upwards would counteract the secular decay of rotation in the upper layers, which would ensure that the rotationally induced magnetic field remains strong and the associated chromospheric activity, hence X-ray luminosity, remains high. The stronger X-ray emission of old overluminous stars implies, in fact, that any such mechanism must be capable of not just maintaining but enhancing that emission as the star ages.

8. Conclusions

The observational data that became available during the last two decades reveal that the population of solar-type stars in the mass range $M \sim 1$ to 1.5 $M_\odot$, represented mostly by F stars, is non-uniform in terms of stars’ stellar evolution rate and also in terms of the direction of the evolution of coronal activity. First, F stars that have been found to be too luminous for their temperature and surface gravity – the overluminous stars – are much older than estimated from the standard stellar evolution models. Second, the X-ray emission of old overluminous stars is on average stronger than that of young stars, which is opposite to the expectations from the commonly accepted evolutionary path of coronal activity for stars in the solar-mass range.

These two findings suggest that standard models of stellar evolution and evolution of stellar activity overlook some crucial physical processes. Recent developments in stellar evolution modeling that include inner rotation and angular momentum transfer as a new factor additional to mass and chemical composition seem to provide the necessary parameters and mechanisms to explain the existence of overluminous stars and their proper-
ties. This is good news. What is not so good is that computing stellar age from comparison of model calculations and observational data is now becoming a task much more challenging than before.

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