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New Candidates for Chromospherically Young, Kinematically Old Stars

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Abstract. One method for estimating stellar ages is based on the chromospheric activity (CA) of a star. Its relation with age arises from the progressive loss of angular momentum a dwarf star experiences over time due to magnetized winds, which decreases stellar rotation. Roughly speaking, chromospherically active objects are expected to be young. At the same time, objects orbiting the Galactic center for long periods tend to increasingly deviate from its initial orbits, determined by the dynamics of the primordial gas that originated them. Thus, stars with an anomalous behaviour in a space velocities diagram are expected to be old. Our work exploits this dichotomy by identifying objects with intense CA and high components in space velocities: chromospherically young, kinematically old objects (CYKOs). A hypothesis that can explain their occurrence is the interaction between stars in short-period binary systems: the outcome of a coalescence would be an object with intense CA and kinematical features inherited from the former pair. In order to verify this scenario, we investigate lithium depletion in stellar atmospheres by searching for observed spectra in literature and by observing candidates at the Pico dos Dias observatory (MG, Brazil). Finally, we have yielded a list with 50 CYKOs.

Resumo. Uma forma de se estimarem idades estelares é baseada na atividade cromosférica (AC) da estrela. A relação com idade surge da progressiva perda de momento angular que com o tempo uma estrela anã experimenta devida a ventos magnetizados, o que reduz a rotação estelar. Grosso modo, espera-se que objetos cromosfericamente ativos sejam jovens. Ao mesmo tempo, objetos orbitando o centro Galáctico por longos períodos tendem a cada vez mais desviar de suas órbitas iniciais, determinas pela dinâmica do gás primordial que os originou. Assim, espera-se que estrelas com comportamento anômalo em um diagrama de velocidades sejam velhas. Nosso trabalho explora essa dicotomia identificando objetos com intensa AC e componentes excêntricas de velocidades espaciais: objetos cromosfericamente jovens e cinematicamente antigos (CroJoCAs). Uma hipótese que pode explicar sua ocorrência é a interação entre estrelas de sistemas binários de curto período: o resultado de uma coalescência seria um objeto com AC intensa e características cinemáticas herdadas do par anterior. Para verificar este cenário, investigamos a depleção do lítio em atmosferas estelares buscando espetros na literatura e observando candidatos a CroJoCAs no Observatório Pico dos Dias (MG, Brasil). Por fim, obtivemos uma lista com 50 CroJoCAs.

Keywords. Galaxy: solar neighborhood – Stars: activity – Stars: chromospheres – Stars: kinematics and dynamics – Stars: abundances

1. Stellar Ages & Chromospheric Activity

The chromospheric activity (CA) of a star is a set of phenomena responsible for dumping mechanical energy into the so called chromosphere, a layer just above (although hotter) than the photosphere. Because of this activity, radiative equilibrium does not explain alone the observed heating (for a comprehensive review on CA, see Hall 2008).

One of the various methods to measure the CA of a star is through the H and K lines from Ca II. Vaughan et al. (1978) introduced the now famous S-index, for the Mount Wilson Observatory HK project, that measured the purely chromospheric emission seen as reversals at the centers of those lines (see e.g. Figure 3 of Schröder et al. 2009). Noyes et al. (1984) updated it into a new index, $R'_{\rm HK}$, that takes into account not only an intrinsic bias that arises due to the star's temperature, but also photospheric contamination in H and K lines reversals, enabling the comparison of the CA of stars with different spectral types.

The relation between CA and age arises from the fact that aging is tightly linked to stellar rotation and magnetic activity, since these features evolve in time (Skumanich 1972). It is well established in literature that for sun-like dwarfs, stellar rotation and magnetic activity tend to decrease with age, due to angular momentum loss through magnetized winds and structural variations on evolutionary timescales, and therefore CA–age relations can be calibrated (e.g. Skumanich 1972; Soderblom et al. 1991; Mamajek & Hillenbrand 2008; Lorenzo-Oliveira et al. 2016), such that one can state that intense CA is a proxy for youth.

2. Stellar Ages & Kinematical Features

Since their birth, stars experience kinematical evolution as they age and go through their orbits around the Galactic center. This evolution results in a statistical correlation known as disk heating (Wielen 1977), a net increase in Galactic space motions with time. Some mechanisms that can explain the fluctuations that a star can encounter when traveling around the Galactic center are summarized in e.g. Almeida-Fernandes & Rocha-Pinto (2018, hereafter AFRP18): encounters with giant molecular clouds, interaction with non-axisymmetric Galactic structures, interactions with satellite galaxies, etc.

In order to quantify this behaviour, stellar space velocities can be derived from proper motions and radial velocities, and can be put in a common reference system, in our case the Local Stantard of Rest (LSR), valid for stars in the solar neighborhood. In a three dimensional motion, stars move around the Galactic center with velocities u, v and w (respectively pointing towards the Galactic center, the direction of rotation and the north pole).

It is easy to qualitatively visualize this dispersion behaviour when stellar ages are plotted against space velocities u, v, w (corrected for accounting solar motion with respect to the LSR) for stars in the solar neighborhood (e.g. Figure 2 from Rocha-Pinto et al. 2004): there is a clear spread towards older chromospheric ages; also when plotting ages against the dispersion values themselves (e.g. Figure 1 from AFRP18). One can derive an age–velocity dispersion relation, and we can state that high space velocities components, i.e. motions that are way faster (or slower) than the LSR, can be associated to old stars.

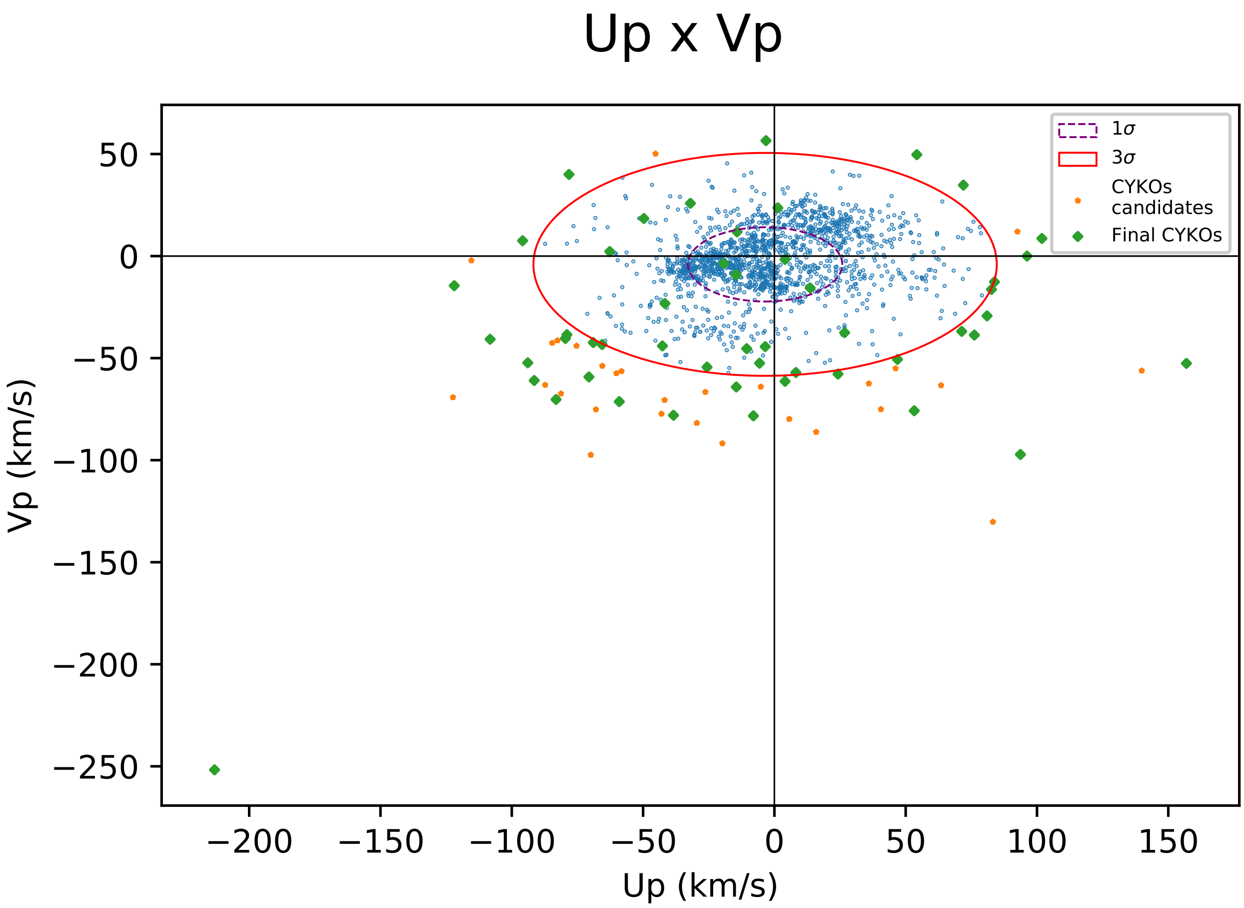

Figure 1. Space velocities diagram for active stars: the full, outer ellipse represents the 3σ dispersion limit for space velocities components. CYKOs candidates are seen outside this line and the final selected ones are plotted as large diamonds. The ones inside the 3σ ellipse were selected from the *w* vs. *v* diagram.

3. Chromospherically Young, Kinematically Old objects

3.1. Formation

The occurrence of active old stars seems at first inconsistent, since single sun-like stars lose angular momentum due to magnetized winds, which in turn leads to magnetic rotational braking and subsequent decrease in its activity. In a paper that where he discusses the space motions of active late-type dwarfs, Soderblom (1990) noticed the presence of these “deviant stars” – as himself called – but assumed they could be products of random processes and did not invest in a further investigation.

A hypothesis that can explain CYKOs occurrence is the coalescence of a short-period pair, as described in Poveda et al. (1997), who refered to them as *red stragglers* in an analogy with the better known blue stragglers. These authors argue that once the close binary system is tidally locked, it will irreversibly evolve to a contact binary and eventually to a single rejuvenated star, with chromospheric activity levels that would mimic those of a young star, but with kinematical features that evolved in time inherited from the former binary. This is explained by orbital angular momentum being transfered into rotational momentum, which keeps the pair active for longer periods than expected for a single dwarf that follows the Skumanich law, whereas the angular momentum loss would be offset by progressive approximation of the pair (Stępień 1995).

Based on this scenario, Rocha-Pinto et al. (2002) also specifically searched for active stars with kinematical features associated to old objects, coining the acronym CYKOs for chromospherically young, kinematically old, and presented a list with 29 of them. The main difference between their work and that of Poveda et al. (1997) is the introduction of a way to identify CYKOs as old stars through their lithium content, which we also exploit in this work, as discussed in section 4.

3.2. Sample and identification

In our work, we adopted a formalism similar to that proposed by Poveda et al. (1997) and followed by Rocha-Pinto et al. (2002) to identify active stars with typical velocities of older ones: after plotting chromospherically active stars in a space velocities diagram, we select the ones lying outside a 3σ limit for dispersion values in each velocity component. We found dispersion values by following AFRP18 (Table 1), which yielded (in km s^{-1}) $\sigma_U = 29.41$; $\sigma_V = 18.21$; $\sigma_W = 14.25$. Since we needed an age to use as input, we turned to the CA-age calibration presented in equation (3) from Mamajek & Hillenbrand (2008) and found the one that is associated to $\log R'_{HK} = -4.75$: 2.55 Gy. This is the activity boundary we set in this work based on the so-called Vaughan-Preston gap, where Vaughan & Preston (1980) reported an apparent lack of stars.

Our sample is composed by stars with known chromospheric activity from three sources: (*i*) a list gathered by one of us (Rocha-Pinto) in the course of other studies, with 1235 entries; (*ii*) the sample presented in Murgas et al. (2013), in a context of searching for moving groups based on stellar activity, with 2529 entries; and (*iii*) the largest compilation we found in literature, by

Boro-Saikia et al. (2018), who showed evidence for questioning the bimodality seen in stellar activity cycles, with 6962 entries; all three sources presented repeated entries. Merging those together yielded a final list of 5175 unique objects with mean CA values.

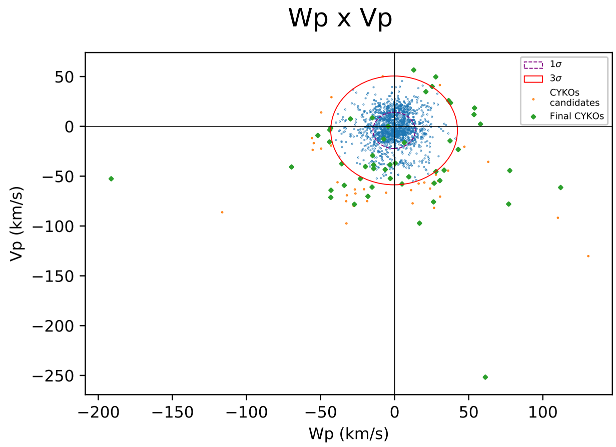

Figure 2. One of our CYKOs candidates (HD152391), observed with the coude spectrograph mounted in at Pico dos Dias Observatory. The shaded region comprises the Li I line, which is nearly absent, indicating a scenario that may corroborate to a coalescence hypothesis.

From those, 2121 were selected for being classified as active ($\log R'_{HK} = -4.75$) and crossed against the Gaia DR2 astrometric solution catalogue (*Gaia Data Release 2. The astrometric solution* 2018) from *The Gaia mission* (2016). We found 1692 having kinematical information, which we used to calculate their space velocities components (u, v, w). Next, following the formalism described in Rocha-Pinto et al. (2002), we plotted these stars in the space velocities diagram shown in Figure 1, for components u vs. v. The inner and outer ellipses were drawn based on dispersion values, respectively 1σ and 3σ for each component, and objects lying beyond them are the selected 93 CYKOs candidates. Finally, we filtered only the stars of spectral types F, G and K, and removed the ones with any binarity flag from SIMBAD. After this process, 50 candidates remained, which are represented by large diamonds marks, and this is our final CYKOs list.

It is important to mention that the large diamonds in Figure 1 represent all CYKOs regardless of their selection criterion, this is why some of them appear inside the outer ellipse. We show in Figure 2 the same plot, but for velocities w vs. v, and the same behaviour can be seen. We clarify that candidates were selected if they appeared outside any of the ellipses, i.e. if an object is outside the ellipse in the UV space but not in the WV space (and vice-versa), it still is considered a CYKO candidate. The stars that were selected from both UV and WV criteria are most likely stars we are looking for, but not the only selected ones.

4. Observing lithium in CYKOs

In order to verify whether the coalescence hypothesis is a valid scenario for CYKOs' formation, we analyze their lithium content, assuming they're old stars that coalesced. Lithium depletion is a well established phenomenon that takes place in stellar atmospheres, characterized by this element's fragility, being destroyed in environments hotter than $T \sim 10^6$ K. As a rule, it's safe to say that old main sequence stars are expected to be lithium depleted, given the fast timescale of the destruction process (Skumanich 1972, and references therein, e.g. van den Heuvel & Conti 1971) in comparison to that of overall stellar evolution.

Spectroscopic observations of CYKOs in the region of the lithium line (λ 6707.8 Å Li I) allow us to confirm whether the coalescence scenario is reasonable, given we expect detect no or low lithium content in these stars. Hitherto, we have observed 5 candidates with the coude spectrograph mounted at 1.6m Perkin-Elmer telescope at the Pico dos Dias Observatory (data currently in reduction phase) and we still have other three observation runs to perform. The signal-to-noise ratio and resolving power we will reach in these observations (respectively, $S/N \gtrsim 100$, $R \gtrsim 10,000$) will most likely not allow us to retrieve reliable stellar abundances, such that we will only be able to discriminate which stars show a relevant amount of lithium in their atmospheres, instead of actually determining how much of this element is present there. This configuration is enough in the light of what this work is supposed to do, which is to qualitatively identify active old stars.

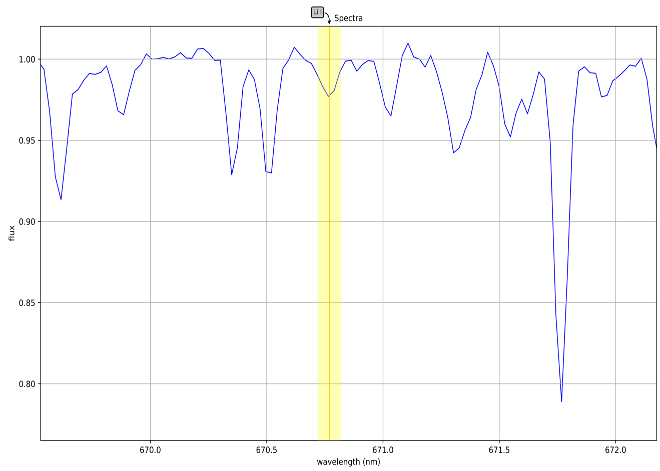

Figure 3. One of our CYKOs candidates (HD152391), observed with the coude spectrograph mounted at 1.6m telescope at Pico dos Dias Observatory. The shaded region comprises the Li I line, which is nearly absent, pointing towards a scenario that may corroborate to the coalescence hypothesis.

We show in Figure 3 a preliminary result with an observed spectrum of the star HD152391, one of our selected 50 CYKOs. Only a small content of lithium can be seen in the indicated shaded region, which is a scenario that can corroborate to the merger between two old (lithium depleted) stars. Soderblom (1990) discussed this "genuinely embarrassing" case, arguing that it is unlikely is has an unrevealed companion that would account for its observed CA, but expected this would be the explantion. He compared this star to a similar one, namely ξ Boo A, in spectral type and CA, and mentioned that in spite of these and other similarities, Herbig (1965) reported that the lithium content in each one was rather discrepant: it was abundant in ξ Boo A but none in HD152391, in agreement with what we can see in 3, at least qualitatively.

5. Future work

With the remaining three observing runs to be performed, we expect to confirm this lack of lithium behaviour in CYKOs, as well as with spectroscopic data available from other databases, e.g. HARPS, FEROS, ESO-Gaia survey, etc.

5.1. Another hypthesis

Apart from the main coalescence scenario we investigate in this work, it's relevant to notice that another testable hypothesis is one as described by Jeffries & Stevens (1996): in order to explain the occurrence of wide binary systems consist of a hot white dwarf and a fast rotating K-dwarf, the authors propose that the low-mass secondary would be spinned up by accreting the slow, massive wind from the progenitor of the white dwarf in a detached configuration. This interaction would lead to an ultra-rapidly rotating dwarf up to 100 astronomical units apart from its white dwarf companion. In that case, we obviously cannot eliminate the stars with any binarity flags, and this is a hypothesis to be further scrutinized soon enough.

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