TUESDAY

The discovery path of the inverse square root of age relations for solar-type stars

Andrew Skumanich
High Altitude Observatory

This talk will describe the discovery path of the inverse square root dependance of a star's age for main sequence stars. It will highlight the analysis of the circumstantial evidence that led to the relation that rotational spin down and magnetic activity decay by the square root law. The temporal history of observed changes in key stellar properties may be measured by various types of 'clocks'. The first clock is the stellar nuclear reaction rate, which gives rise to the luminosity - or power - radiated by a star. Given the mass of a star and its nuclear composition the physics dictates the progression of its luminosity, as well as it's radius (or equivalently the surface temperature or color). These two parameters can be located on the famous Hertzsprung –Russell diagram that relates luminosity with color for any observed star. As the reaction rate begins to deplete the nuclear fuel the star begins to migrate across the HR diagram. The second clock deals with stellar kinematics. The turbulence within interstellar clouds decays with time so that stars formed at an earlier epoch will have larger velocities than those formed later. In addition, as Spitzer, Schwarzschild and Osterbrock have shown, subsequent collisions of stars with high velocity clouds increase their velocities. Hence lower velocities indicate younger ages. The third clock deals with the level of magnetic energy activity that decays by dissipation. Such processes produce stellar coronae, with their associated magnetized stellar winds that lead to angular momentum loss. Magnetic activity also leads to chromospheres that age with time. Another associated age indicator is the gradual enrichment of the 'metallic', eg Carbon, Calcium, etc. , content of the interstellar clouds due to supernova explosions.

Modeling Stellar Activity-rotation Relations in Unsaturated Cool Stars

Alison Farrish
NASA Goddard

We present recently published work on the X-ray emission-rotation relationship for a set of modeled unsaturated cool stars (Rossby numbers Ro > 0.1). An empirical surface flux transport model developed from solar observations is applied to reconstruct the stellar activity-rotation relationship. This empirical flux transport model incorporates modulations of magnetic flux strength consistent with observed solar activity cycles, as well as surface flux dynamics consistent with observed and modeled stellar relationships. We find that for stellar flux models corresponding to a range of $0.1 <$ (Ro/RoSun) < 1.2, the LX/Lbol versus Ro relation matches well the power-law behavior observed in the unsaturated regime of cool stars when the evolution of Lbol with time is accounted for by incorporating Skumanich-like spindown. The success of our flux transport modeling in reproducing the observed activity relationship across a wide range of late-F, G, K, and M stars suggests that the photospheric magnetic fields of all unsaturated cool stars exhibit similar flux emergence and surface dynamic behavior, and may hint at possible similarities in stellar dynamo action across a broad range of stellar types.

Solar- and Stellar-Wind Torques from Observations and Theory

Sean Matt
University of Exeter

I will highlight some recent results on quantifying stellar-wind angular-momentum loss, obtained from simplified MHD simulations, from in situ observations of the solar wind, and somewhat less directly from rotational evolution models and observations. We are still working to reconcile the results from each of these techniques, but the process gives us valuable insights into the physics of stellar winds and how magnetism and mass loss varies with stellar mass and time.

Star Clusters Reveal Spin-down Temporarily Stalls

Jason Curtis
Columbia University

Recent measurements of rotation periods in the benchmark open clusters Praesepe (700 Myr), NGC 6811 (1.0 Gyr), NGC 752 (1.4 Gyr), and Ruprecht 147 (2.7 Gyr) demonstrate that, after converging onto a tight sequence of slowly rotating stars in mass-period space, stars apparently stop spinning down temporarily. Hints of this phenomenon have been present in the literature focused on younger open clusters for a long time, but the definitive evidence only emerged once the 1-Gyr-old K dwarfs of NGC 6811 were found rotating at the same rate as the 700-Myr-old ones in Praesepe. The data for the older clusters also show that the duration of this epoch of stalled spin-down increases toward lower masses, such that early-M dwarfs remain stalled for at least one Gyr. This temporary pause tends to flatten out older mass versus rotation sequences compared to the more steep sequences seen in younger clusters. To accurately age-date isolated low-mass stars in the field, gyrochronology formulae must be modified to account for this temporary pause in spin down. Empirically tuning a core-envelope coupling model with open cluster data can account for most of the apparent stalling effect. However, alternative explanations, e.g., a temporary reduction in the magnetic braking torque, have not yet been ruled out.

Constraining Stellar Rotation at the Zero-Age Main Sequence

Stephanie Douglas
Lafayette College

As stars approach the main sequence, they contract and spin more rapidly; once they reach the main sequence, they stop contracting and their spin speed decreases. This spin-down is thought to be caused by angular momentum lost via stellar winds, but we lack observational constraints on the rotation of Solar-type zero-age main sequence (ZAMS) stars to test the behavior of models at this critical age. We use TESS full-frame images to measure rotation periods (P_{rot}) for stars in five young open clusters in the Southern Sky. Out of 1503 stars with TESS data, we measure rotation periods for 1046; this is a four-fold increase over previous ground-based period samples. We compare the 187 Solar-type rotators to 5 models for stellar angular momentum evolution, and find that they fail to predict the fastest rotation periods at this age. We have also surveyed 35 FGK rotators in IC 2391 using speckle imaging at Gemini-South, and detect 4 candidate companions. We will present our results on the rotation of Solar-type stars at the ZAMS, as well as preliminary results on the impact of multiplicity on the ZAMS P_{rot} distribution.

Low-Mass Stellar Rotation Rates from 1- 790 Myr

Luisa Rebull
Caltech-IPAC

In recent years, we have been using K2's high precision photometry to probe stellar variability and stellar rotation to lower masses and lower amplitudes than has ever been done before. Younger stars are generally more rapidly rotating and have larger star spots than older stars of similar masses. K2's large field of view was able to monitor a significant fraction of many nearby clusters and associations; some of the nearest associations can only be monitored by TESS, which observes 85% of the sky. We present rotation rates from a TESS study of stars in the ∼15 Myr old Upper Centarus-Lupus (UCL)/Lower Centaurus-Crux (LCC) association, in context with the rotation rates from K2.

Pile-ups in the Temperature-Period Distribution: Futher Evidence for Modified Spin-down in Sun-like Stars

Trevor David
Flatiron Institute

Evidence is growing that standard spin-down models can not reproduce the observed stellar rotation periods. Leveraging high-precision spectroscopic surveys of the Kepler field I demonstrate the existence of pile-ups at the long- and short-period boundaries of the temperature-period distribution for main-sequence stars more massive than the Sun. These pile-ups can be successfully modeled as curves of constant Rossby number, and we show that stars in the long-period pile-up have a broad range of ages. These observations can not be explained by standard spin-down models but instead were predicted by van Saders et al. 2019 as a consequence of weakened magnetic braking. The short-period pile-up is not a prediction of the weakened magnetic braking hypothesis, but may instead be related to a phase of delayed spin-down due to core-envelope coupling previously proposed by Curtis et al. 2020 to explain the overlapping rotation sequences of low-mass members of differently aged open clusters. I will discuss the implications of these results for stars like the Sun and the limitations the pile-ups present to the field of gyrochronology.

The Role of Magnetic Complexity in the Rotation Evolution of Cool Stars

Cecilia Garraffo
Center for Astrophysics, Harvard & Smithsonian

Studies of the rotation periods of solar-like stars in young open clusters have revealed a bimodal distribution that has proven difficult to explain under existing magnetic braking models. Recently, there has been growing agreement that the morphology of the magnetic field on the stellar surface (the magnetic complexity) can be important in controlling stellar spin-down rates. In this talk, I will discuss the role of magnetic complexity on stellar spin-down evolution and how it can provide the missing piece to solve the bimodal rotation period puzzle. I also point to the long-standing problem of the cataclysmic variable period gap that can also be explained in terms of magnetic complexity. I touch on what magnetic complexity means in the context of Gyrochronology, and what challenges we face moving forward.

Connecting the disk dispersal phase to magnetic morphology-driven stellar spin down

Kristina Monsch
Smithsonian Astrophysical Observatory (SAO), Harvard & Smithsonian

The high energy radiation emitted by young stars can have a strong impact on their subsequent rotational evolution at later stages. This is because XEUV-driven photoevaporation is one of the major drivers of the dispersal of circumstellar disks, which surround all newly born stars during the first few million years of their evolution. Since the photoevaporative mass loss is mainly a function of stellar X-ray luminosity, the lifetimes of circumstellar disks are primarily set by the X-ray emission of their central star. Stellar rotation and X-ray activity are therefore tightly coupled, as the circumstellar disk prevents the star from spinning up as it contracts through the disk-locking phase. Using the magnetic morphology-driven stellar spin-down model by Garraffo et al. (2018), we show that the disk-locking phase has a profound impact on the subsequent rotational evolution of young stars. By assuming that the lifetimes of circumstellar disks are mainly determined by the X-ray luminosity of their central stars at young stages, we find that the bimodal rotation period distribution of a number of older open clusters, such as Pleiades or Hyades, can be successfully recovered.

Are the Skumanich relations the same for chromospheric and coronal diagnostics?

Jeffrey Linsky
JILA/University of Colorado and NIST

The age dependence of stellar chromospheric and coronal emission has been measured in optical and UV emission lines and in X-ray emission. Although all of these diagnostics share a common pattern of saturation for young stars and logarithmic decay for older stars, the detailed patterns are not the same for the different diagnostics and different spectral types. I will show that the ratio of chromospheric emission as measured by Lyman-alpha flux to coronal emission as measured by X-ray flux is the same for F, G, and K stars. However the pattern is different for M stars and especially late-M stars where the Lyman-alpha emission is relatively weak compared to the X-ray emission. As shown in an analysis of 79 stars observed by HST and Chandra or XMM, the L(Lyman-alpha)/L(bol) ratio increases steadily with decreasing effective temperature for stars younger than 450 Myr, but the L(X)/L(bol) saturates at 70-90 Myr for stars cooler than 5400 K. For older stars both L(X)/L(bol) and L(Lyman-alpha)/L(bol) increase steadily to lower effective temperatures. The different saturation times and coronal/chromospheric flux ratios with spectral type are essential input when evaluating Skumanich relations among different stars.

How does magnetic activity depend on stellar metallicity?

Victor See
ESA, ESTEC

Understanding how the magnetic activity of low-mass stars depends on their fundamental parameters is an important goal of stellar astrophysics. Previous studies suggest that the stellar mass and rotation period both play important roles in determining the overall activity level of a star. However, until recently, we have had little information on the role of metallicity. In this talk, I will discuss how magnetic activity scales with stellar metallicity. Specifically, I will use photometric variability as a proxy for magnetic activity. Using a sample of over 3000 low-mass stars in the Kepler field, I will demonstrate that, at fixed stellar mass and rotation, more metal-rich stars are generally more magnetically active. I will also discuss the important implications of this result for recovering rotation periods from light curves as well as for rotation period evolution.

Lithium In Time (invited review)

Marc Pinsonneault
Ohio State University, Dept. of Astronomy

The light element lithium is fragile in stars, making it a sensitive diagnostic of mixing processes in stellar interiors. The seminal Skumanich 1972 paper provided a powerful clue, with a correlation between stellar spin down and lithium depletion. In this review I will summarize the key observed features of lithium depletion in sun-like stars, outline the ingredients for a successful theoretical explanation, and critique how well our current models succeed. Lithium is observed to deplete on the main sequence, at a rate that declines with age, by different amounts in stars of the same mass composition and age, across a wide range of convection zone depths. Models that do not include rotation have great difficulty in reproducing these features. Rotationally-induced mixing is a promising framework, but modern models struggle to reproduce the observed pattern. The solution likely lies in a deeper understanding of the physics of internal angular momentum transport in stars, which still lacks a consensus solution.

Rotation and Li in a recently discovered young cluster (that also hosts an exoplanet)

Elisabeth Newton
Dartmouth College

The synergy of publicly-available datasets from all-sky surveys enables rapid discovery and characterization, using the Skumanich relations, of new stellar clusters. "Group X", a compact cluster with a few hundred members, was recently discovered using data from Gaia and has yet to be fully characterized. We used photometry from TESS and ZTF to independently measure stellar rotation periods for cluster members, which show a clear rotation sequence. We also obtained high resolution optical spectra from McDonald Observatory and measure Li equivalent widths. I will present our measurements and age determination for the cluster, and I will highlight how our team has been using similar methods to determine the ages of young, planet-hosting stars in both known and new young associations.

Constraining evolutionary models and ages of low mass stars with Li-depletion and rotation

Alexander Slater Binks
Massachusetts Institute of Technology, Kavli Institute

Standard stellar models are clearly at odds with colour-magnitude diagrams (CMDs) and Li-depletion patterns of pre main sequence (PMS) stars in clusters. Mounting evidence suggests inflation in low-mass stars - caused by strong dynamo-driven magnetic fields and/or cool starspots - leads to older inferred isochronal ages, in turn delaying the onset of Li-depletion, prompting a new generation of ”magnetic models”. By kinematically selecting high-probability members of 5 clusters from the Gaia-ESO Survey, with ages between ∼5-150 Myr we examine both standard and magnetic models by fitting isochrones and visually assessing the Li-pattern. We find: standard models provide under-luminous fits at low-masses and can’t capture the early stages of Li-depletion; magnetic models are consistently 1.5-2 times older and better match Li-depletion; strong degeneracy between magnetic activity and age. Using TESS 30-min lightcurves we compiled rotation periods. Among the K-stars in the older clusters we find the brightest and least Li-depleted are the fastest rotators, demonstrating the classic “Li-rotation connection” for the first time at ∼35 Myr in NGC 2547, and find some evidence that it exists in the early M-stars of NGC 2264 at <10 Myr.

WEDNESDAY

Evidence for weakened magnetic braking in middle-aged stars

Jennifer van Saders
University of Hawaii

The Kepler mission provided the first significant sample of old stars with both measured rotation periods and precision ages, opening a path to studying the spin-down of stars in the latter half of their main sequence lives. Several works have now shown that these intermediate-age and old stars have defied expectations, and appear to be rotating faster than extrapolations of standard spin-down relations would predict: magnetic braking in the latter half of the main sequence appears to be dramatically reduced. If such weakened magnetic braking is indeed present, it limits the utility of period-age relations in old stars, and may signal a fundamental shift in magnetism or mass loss that occurs in middle-aged stars. I will discuss the lines of evidence that support the claim of weakened magnetic braking, datasets that appear to refute it, and future tests of the presence and origin of such a phenomenon.

Statistical Fitting of Rotational Evolution Models

Angela Breimann
University of Exeter

Rotational evolution models (REMs) are typically compared to observed datasets by-eye, a method which is subject to bias and not easily automated. We present our two-dimensional tau squared (τ^2) statistic and its application to REMs and cluster data in the period-mass plane. The statistic simultaneously considers all cluster rotation data in its goodness of fit, allowing for the data-driven improvement of REMs. In tuning REMs to the data and minimising τ^2, we can constrain stellar ages and the physics of stellar magnetic activity and winds, highlighting where model assumptions fail. We demonstrate the technique by finding the best-fitting gyrochronology age for Praesepe. We then systematically vary three parameters in the torque law. The resulting REMs, which represent the best-possible fitting form of this torque law, are statistically improved on previous REMs with similar formulations, but are still unable to simultaneously describe the observed rotation distributions of the lowest masses and the shape of the converged sequence for higher masses. Further complexity in REMs is thus required to accurately describe the data, and we present our progress in fitting these to clusters.

Chemical composition and stellar spin-down

Louis Amard
CEA, France

As shown already by Skumanich in 1972, the spin-down of main sequence cool stars with time can be used as a tool to provide stellar ages under certain conditions. Large photometric surveys such as Kepler, TESS or even GAIA, thus relies on rotation period measurement to estimate the age of cool main sequence stars. Intriguingly, a sequence of cool slower-than-expected rotators in the HR diagram was discovered in Kepler data, suggesting a deviation from classical gyrochronology due to an unknown source. Recently, Amard & Matt (2020) and Claytor et al. (2020) showed that metal-rich stars are likely slower rotators on the main sequence due to being cooler and having thicker convective envelope. Using a compilation of mid-to-high resolution spectroscopic surveys of the Kepler field (LAMOST, APOGEE), we are now able to explore the effect of chemical composition on a population of rotating stars. Combined with Kepler and Gaia observations, and a grid of rotating stellar evolution model over a large range of mass and metallicity, this new sample allows us to reproduce the feature suggesting a deviation to usual spin-down and, to a later extent, to explore and constrain the link between chemical composition, mass, rotation and activity.

Architectures of rotating star-planet systems: Comparing theoretical predictions to observations

Rafael A. Garcia
DAp/CEA-Saclay (France)

In 2013, McQuillan et al. compared stellar rotation periods ($P_{\rm rot}$) with orbital exoplanet periods showing a dearth of close-in planets. In this work we revisit this study using the full Kepler data set with an improved rotation period extraction pipeline including ML classifiers and taking into account only confirmed ones. The results are then confronted to the synthetic population obtained from the star-planet secular evolution code ESPEM, which takes into account the tidal and magnetic interactions as well as the influence of stellar winds. Comparing the outcome of ESPEM's $P_{\rm rot}$ with either the full set of confirmed planets or the ones in which a $P_{\rm rot}$ has been measured, there is no biases between them, meaning that this last dataset is a good statistical representation of the orbital periods of all the exoplanets systems detected to date. When comparing Kepler planets hosts with measured $P_{\rm rot}$ with ESPEM, we find a general qualitative good agreement. Nevertheless, ESPEM predicts too many close-in planets. We will discuss the possible reasons for this mismatch in terms of: 1) the potential missing ingredients in the star-planet interactions, 2) the influence of the initial post-disk distribution, and 3) any statistical biases.

Weakened magnetic braking supported by new asteroseismic rotation rates of Kepler dwarfs

Oliver Hall
European Space Research and Technology Centre - ESA ESTEC

Studies using asteroseismic ages and rotation rates from star-spot rotation have indicated that standard age-rotation relations may break down roughly half-way through the main sequence lifetime, a phenomenon referred to as weakened magnetic braking. While rotation rates from spots can be difficult to determine for older, less active stars, rotational splitting of asteroseismic oscillation frequencies can provide rotation rates for both active and quiescent stars, and so can confirm whether this effect really takes place on the main sequence. In this talk, I'll show how we obtained asteroseismic rotation rates of 91 main sequence stars showing high signal-to-noise modes of oscillation. Using these new rotation rates, along with effective temperatures, metallicities and seismic masses and ages, we built a hierarchical Bayesian mixture model that showed that our new ensemble more closely agreed with weakened magnetic braking, over a standard rotational evolution scenario.

A Study of Stellar Spins in Open Clusters

Brian Healy
Johns Hopkins University

Stars in open clusters offer unique insight into the outcomes of star formation through their assumed coeval formation. These stars' shared age, metallicity, and formation environment make each cluster a benchmark in temporal, chemical, and dynamical evolution. Among the quantities that offer a glimpse into a cluster's past is the projected inclination, i.e. the projected angle between a star's rotation axis and the observer's line of sight. In this talk summarizing my PhD thesis research, I will describe our determination of the projected inclinations of stars in open clusters to infer the initial conditions of their formation via the synthesis of rotation periods from Kepler and TESS, publicly available spectroscopic rotational broadening measurements, and broad-band stellar photometry. I will describe our determination of spin-axis distributions consistent with isotropy or moderate alignment for NGC 2516 (Healy & McCullough 2020), the Pleiades and Praesepe, as well as a possible subset of aligned stars in M35 (Healy, McCullough & Schlaufman 2021). I will also present preliminary results from the final stage of the study and comment on the additional insights we draw from the entire sample of 16 open clusters.

Novel gyrochronology tests with wide-separation binaries

Diego Godoy-Rivera
Instituto de Astrofisica de Canarias (IAC)

Gyrochronology is the technique that uses rotation periods to derive stellar ages via age-rotation relations. If properly calibrated, its potential applications to Galactic, stellar and exoplanetary astrophysics are far-reaching. With the continuous increase of the number of stars with measured rotation periods, it has become imperative to comprehensively test gyrochronology and understand its limits. In this talk I will present a novel method that tests the modern age-rotation relations in under-explored domains using wide binary stars. The components of a given binary are co-eval and taken together they can provide exquisite gyrochronology assessments. By applying this method to a sample of Kepler-field binaries and star clusters we find that: 1) the commonly used age-rotation relations do have predictive power in identifying co-eval populations of field stars; 2) they achieve the best results when used in young clusters (< 1 Gyr); 3) their performance decreases when used in field wide binaries and older clusters. All in all, better calibrations are needed, particularly in the regime of old ages ($>$ few Gyr). This work sets up the stage for decisive gyrochronology assessments in the era of ever-expanding space-based photometry.

Angular momentum transport on the red giant branch: impact of the stellar mass

Charlotte Gehan
Max Planck Institute for Solar System Research, Göttingen, Germany

Red giants are asteroseismic targets of high interest as their mixed modes provide us with a direct view on the physical conditions in their core, including their core rotation, which is not the case for solar-type pulsators on the main sequence. However, models face difficulties in explaining the low values measured for the core rotation rate of stars on the red giant branch. Hence, we still need to investigate the physical mechanisms transporting angular momentum inside red giants. We have at hand core rotation rate measurements for almost 900 low- and intermediate-mass stars on red giant branch (Gehan et al. 2018), which can be used to constrain the angular momentum transport in stellar models. I will present a preliminary modelling work aiming at characterizing how the efficiency of the angular momentum extraction from the core varies with the degree of evolution along the red giant branch, and how it depends on the stellar mass. To that end, we combine profiles of the moment of inertia computed with the MESA evolution code with information on the rotation profile in the core brought by measurements, for different stellar masses and at different evolution stages on the red giant branch.

Detecting Starspots in APOGEE spectra

Lyra Cao
The Ohio State University

Active late-type stars have large fractions of their surface covered with starspots. We fit APOGEE DR16 spectra with 2 temperature components, and use this technique to infer star spot filling fraction and temperature contrast for single stars in open clusters and associations. We recover robust star spot signatures in young and active stars, and the expected null result in old and inactive ones. We find a strong relationship between star spot filling fraction and Rossby number. The filling fraction saturates for rapidly rotating stars and sharply declines at a critical Rossby number, which indicates that the activity saturation phenomenon is related to a saturation in mean surface field strength. We find a Skumanich-like relationship between filling fraction and age for the M dwarfs, and clear correlations between starspots and activity indicators (Halpha, Ca II, X-ray luminosity). Using the young benchmark system Upper Sco, we discuss the effects of starspots on non-spotted young star temperatures, radii, and ages. Finally, we discuss the projected star spot yields in APOGEE DR17 and Milky Way Mapper.

Characterizing magnetic activity through the lens of sub-subgiant stars

Natalie Gosnell
Colorado College

As our knowledge of stellar evolution unfolds the complexities introduced by magnetic stellar activity become more apparent. One example is seen in sub-subgiants, magnetically active stars with starspots that sit below the subgiant branch and red of the main sequence on a cluster color-magnitude diagram. Here we focus on S1063, a P_{rot}otypical sub-subgiant in M67 with a rotation period of 23.5 days. Sub-subgiants exhibit strong variable light curves as starspots rotate in and out of view. We benchmark the variability observed in a multi-year light curve using a two-temperature spectral decomposition technique, finding the spot filling factor varies between 20% to 45% over four years. This analysis brings to light some important nuances when considering observational and theoretical comparisons of spotted stars. We are currently expanding this study by observing field sub-subgiants using IGRINS with contemporaneous or near-contemporaneous TESS coverage. This technique opens the possibility of characterizing the surface conditions of many more spotted stars than previous methods, allowing for larger studies capable of testing theoretical models of magnetically active stars.

Sub-subgiants in Gaia EDR3: A New Window Into the Strange Evolution of Active Giant Stars

Emily Leiner
Northwestern University/CIERA

Sub-subgiant stars (SSGs) fall below the subgiant branch and/or red of the giant branch, an area of the color-magnitude diagram (CMD) not populated by standard stellar evolution tracks. Only 65 SSGs have been identified in the literature, all found in star clusters. These SSGs are short-period binary systems with giant star primaries that are rapidly rotating and magnetically active. One explanation for SSGs is that their strong magnetic fields inhibit convection, creating giants with inflated radii and cooler surface temperatures— a similar effect as is observed in active M-dwarfs. By cross-referencing a catalog of known active giants in the field with Gaia photometry and parallaxes, we can now precisely position a large sample of active giants in a CMD. Out of a sample of 1723 active giants, 448 fall below a 14 Gyr isochrone, classifying them as field SSGs. This result demonstrates that active stars often evolve to be much redder and fainter giants than predicted by standard models. I will discuss the rotation period and CMD distributions of this new SSG population, and what these teach us about the interplay between rotation, magnetic activity, and the evolutionary trajectory of active stars beyond the main sequence.

Wilson-Bappu 2022

Thomas Ayres
University of Colorado (CASA)

The Wilson-Bappu Effect (WBE) has long fascinated astronomers (well, at least a few of us) and the general public (see Season 3, Episode 21 of the "Big Bang Theory" [viewer discretion advised]). O.C. Wilson and M.K.V. Bappu made the original discovery in the mid-1950's: a striking systematic correlation between the absolute visual magnitudes of late-type stars and the widths of their 395 nm Ca II H & K chromospheric emission cores as measured on photographic plates. The Ca II width-luminosity relation tracks seamlessly from intrinsically faint red dwarfs to the most luminous yellow supergiants. Initially attributed to chromospheric kinematics, the WBE is now seen as a consequence of an intricate interplay between outer-atmosphere heating, hydrogen ionization and surface gravity. This is a progress report on a new effort to analyze the existing vast collection of HST NUV spectra of the analogous 280 nm Mg II h & k resonance lines, to re-script the Wilson-Bappu story for the modern era.

Building magneto-chronometers for solar-like stars: The state-of-the-art, limitations, and future research challenges

Diego Lorenzo-Oliveira
Universidade de São Paulo

In this talk, I will discuss the improvements in magnetic age-dating techniques of solar-type stars since the seminal work of Skumanich (1972). Then, I will highlight the main features of this approach and its connection to the underlying magneto-rotational evolution scenario. Finally, I will show the impact of different variables on age-activity calibrations (mass, metallicity, and magnetic variability) and possible pathways to derive more robust magneto-chronometers for solar-like stars.

Magnetic activity evolution on the main sequence from the Kepler observations

Savita Mathur
Instituto de Astrofisica de Canarias

The evolution of rotation and magnetic activity of solar-like stars is key to improve our knowledge of stars (e.g. ages). Several spectroscopic surveys have aimed to characterize the magnetic activity of solar-like stars in order to put the Sun into context and in time. By investigating the magnetic activity of other stars in a different parameter space, we can provide additional constraints to dynamo models as a function of stellar age and spectral type. The recent catalog of rotation periods and photometric magnetic activity proxies for more than 55,000 stars observed by the Kepler mission opens the possibility to study the evolution of surface magnetic activity of solar-like stars. We will present a sample of main-sequence stars where we compare the Sun to Sun-like stars. We also find that the magnetic activity of the Sun is comparable to the one of stars with properties very similar to the Sun. We also compute ages based on models that take into account the weakened magnetic braking theory observed in the Kepler asteroseismic sample. This allows us to study the evolution of magnetic activity as a function of Rossby number and age, providing a more complete picture to understand the dynamical changes on the main sequence.

Stellar Cycles in Fully Convective M Dwarfs: Astronomy Beyond a Funding Cycle

Andrew Couperus
Georgia State University

As part of ongoing efforts by the REsearch Consortium On Nearby Stars (RECONS, www.recons.org) to characterize the Sun's neighbors, we explore long-term stellar activity cycles in partially and fully convective M dwarfs using more than two decades of RECONS time series photometry at the CTIO/SMARTS 0.9m telescope. Here we showcase light curves for approximately 20 high-quality and candidate M dwarf stellar cycles in our data, with cycle periods spanning roughly 5-30 years. These cycles are being analyzed using a Gaussian Process-based method under development that maps periodic signals created simultaneously by long-term spot cycles and short-term rotation activity. The vast majority of these observed cycles are hosted by fully convective stars, comprising a unique and significant collection. Work is ongoing to expand the sample of detected cycles and to explore the implications of these cycles for stellar dynamo theory in the fully convective regime. Such efforts will help us better understand the overall magnetic activity of fully convective stars, a key aspect for exoplanet detections and habitability. This work has been supported by the National Science Foundation and the SMARTS Consortium.

A Comprehensive Study of the Rotation-X-ray Activity Relation for Praesepe and the Hyades

Alejandro Nunez
Columbia University

X-ray observations of low-mass stars in open clusters are critical to understanding the dependence of magnetic activity on stellar properties and its evolution. Praesepe and the Hyades are among the best available laboratories for examining the dependence of magnetic activity on rotation. We present an updated study of the rotation-X-ray activity relation in the two clusters. We updated membership catalogs that combine pre-Gaia catalogs with new Gaia-based catalogs, resulting in the most comprehensive catalogs: 1739 Praesepe and 1315 Hyades stars. We collected X-ray detections for cluster members, for which we analyzed, re-analyzed, or collated data from ROSAT, Chandra, Neil Gehrels Swift, and XMM-Newton observatories. We have detections for 326 Praesepe and 462 Hyades members, of which 273 and 164, respectively, have rotation periods –an increase of 6x relative to what was previously available. We find that at 700 Myr, only M dwarfs remain saturated in X-rays and have no evidence for supersaturation. We also find a Rossby-fractional X-ray luminosity (Lx/Lbol) relation in unsaturated members characterized by a power-law with index –2.3. Lastly, we find no difference in the coronal parameters between binary and single members.

THURSDAY

Gyro-Kinematic Ages for around 30,000 Kepler Stars

Yuxi Lu
Columbia University/AMNH

Gyrochronology is a precise way to estimate stellar ages for low-mass stars, as they spin down rapidly due to their deep convection zones and strong magnetic fields. However, calibrating empirical gyrochronology relations for low-mass stars is difficult. These stars are faint and hard to observe, and most age-dating methods cannot provide large samples of precise or accurate stellar ages for calibration. We calculate ages for Kepler F, G, and crucially K and M dwarfs, using their rotation and kinematic properties. We identify coeval stars by grouping them according to rotation period and CMD position, which are both age-indicators. We apply the simple assumption that the velocity dispersion of stars increases over time and adopt an age–velocity–dispersion relation (AVR) to estimate average stellar ages for groupings of coeval stars. With this technique, we are able to estimate stellar ages for clusters and asteroseismic stars with an RMS of 1 Gyr and 0.3 Gyr respectively. We provide kinematic ages for around 30,000 G, K, and M dwarfs observed by Kepler. This is one of the largest samples of relatively precise ages for low-mass stars available, and it could be used to calibrate other dating methods such as gyrochronology.

A 4-Gyr M Dwarf Gyrochrone from CFHT/MegaPrime Monitoring of the Open Cluster M67

Ryan Dungee
University of Hawaii

We present a new sample of stellar rotation periods for late K and early M dwarfs belonging to the open cluster M67. Using Gaia EDR3 parallaxes and proper motions for cluster membership, and Pan-STARRS (PS1) photometry for binary classification, we build this catalog of M dwarf rotation periods from a campaign of monitoring M67 with the Canada France Hawaii Telescope's MegaCam. The rotation periods ($P_{\rm rot}$) that we report are calculated from Lomb-Scargle periodograms. Moreover, we derive effective temperatures for each star from their PS1 r-i colors and provide a polynomial fit to the color-period sequence observed in our data. We compare this observed sequence to the predictions of various gyrochronological models in the literature and find that the best match is a Skumanich-like spin down applied to the stars of Ruprecht 147. This suggests that, for spectral types K7 to M0, once a star resumes spinning down a simple model of $P_{\rm rot} \sim t^{0.62}$ is sufficient to describe their rotation evolution, at least through the age of M67 (4 Gyr).

Optical and UV Variability in the Far Ultraviolet M-Dwarf Evolution Survey

Girish Manideep Duvvuri
CU-Boulder/CASA/LASP

The Far Ultraviolet M-Dwarf Evolution Survey (FUMES) was initially a Hubble program designed to complement the MUSCLES treasury program by characterizing the UV emission of young M dwarfs to determine the evolutionary history of coronal heating and high energy emission of low-mass stars. The survey mandate has since been expanded with the addition of optical spectroscopy and X-ray observations to improve our understanding of how coronal heating relates to the chromosphere and transition region. This talk will present early results demonstrating the relationships between hourly variability of the Balmer series and Ca HK lines, UV variability, and the rotation periods of low-mass stars.

A unified approach to M dwarf ages

Rocio Kiman
Kavli Institute for Theoretical Physics (KITP), UC Santa Barbara

Estimating ages of M dwarfs, the lowest mass stars in the Galaxy, is a current unresolved problem in Astrophysics. In this talk I will describe the method we developed to estimate ages for M dwarfs. This method consists of combining different age indicators in a Bayesian framework to achieve a precise age measurement. The age indicators we used are: 1) position in the color-magnitude diagram, 2) 3D kinematics, 3) magnetic activity, measured by the Halpha emission line of the spectrum. Using the age-relation for these parameters we developed mdwarfdate: an open source Python code that estimates ages of M dwarfs. We confirmed the robustness of the code by testing it on a simulated sample of stars, and examining a set of age calibrators. Using this method, we estimated ages for a sample of field M dwarfs with rotation period measurements. We found that for stars of similar mass which are older than 3 Gyr old according to our method, some stars are inactive and slow rotators (order of 50 days), while others are active and fast rotators (around 1 day). We conclude that our method to estimate M dwarf ages is working, but with large uncertainties which could be improved for inactive stars by including rotation period in the method.

Measuring the Current Angular Momentum-Loss Rate of the Sun

Adam Finley
CEA Paris-Saclay

The Skumanich-relation of spin-down for Sun-like stars has been challenged in recent years by the detection of stars (older than the Sun) with faster than expected rotation rates. In addition, recent rotation period observations indicate a stalling of the spin-down for younger stars, around the age of the Praesepe (670Myrs). So, it is clear that there is more structure, in the rate of spin-down for Sun-like stars during the main-sequence, than given by the Skumanich-relation. As a weakened spin-down is expected around the solar-age, a measurement of the current solar Angular Momentum (AM) loss rate could prove useful in distinguishing the various models of rotation-evolution that are now available. Our ability to measure the solar wind AM flux has improved with the addition of Parker Solar Probe (PSP) and Solar Orbiter (SO) to the constellation of Sun-focused missions. PSP is sampling the solar wind closer to the Sun than ever before, and is set to pass below the Alfven surface (a critical distance for the AM loss rate). I will discuss the most recent AM flux observations from both PSP and SO, and highlight some of the difficulties in extrapolating local measurements of the solar wind to the global AM loss rate of the Sun.

Fast and automated detection of short-period rotators in TESS

Isabel Colman
American Museum of Natural History

TESS has collected light curves for millions of stars across the whole sky, presenting a treasure trove of data and a rich opportunity to measure stellar rotation periods, which could provide opportunities to calibrate gyrochronology relations, especially for low-mass stars, where rotational evolution is still poorly understood. TESS presents a new set of challenges for stellar rotation studies, and as new data is constantly being collected, it's imperative to build a framework for the fast and reliable analysis of light curves. In addition, specialized vetting techniques are crucial for constructing large catalogs of high-fidelity rotation period measurements with TESS. We introduce Spinneret, a pipeline for the automated detection of rotation periods from single-sector TESS light curves. Spinneret utilizes the Lomb-Scargle periodogram and an autocorrelation function for measurement, a random forest algorithm for vetting, and is optimized for the detection of short periods. We present an overview of the construction and training of the Spinneret pipeline, and initial results from the analysis of all TESS 2-minute sectors.

Rotational Characterization of TESS Stars with Deep Learning

Zach Claytor
University of Hawaii

The TESS mission has the potential to probe stellar rotation in millions of stars across the entire sky, but mission systematics—instrumental noise, observing gaps, and changes in detector sensitivity—have prevented recovery of rotation periods longer than 13.7 days. I used deep learning to see through TESS systematics and recover periods from year-long light curves. My approach uses a training set of synthesized light curves from realistic star spot evolution simulations, with real light curve systematics from quiet TESS stars. Evaluating the network on real TESS data, I recovered periods for 20,000 cool dwarfs. The period distribution resembles the Kepler and K2 distributions, including periods up to 90 days. Using gyrochronology, I estimated masses, ages, and other fundamental stellar parameters for 1,000 TESS stars with APOGEE spectroscopy. We combine this with a similar sample from Kepler and show that we can use rotation-based ages to recover Galactic chemical evolution trends previously seen only in stars more massive or more evolved than the Sun. With rotation periods across the entire sky, we can characterize stars along many more lines of sight than before, enabling detailed study of the Galaxy's stellar populations.

An Automated, Autocorrelation-based Algorithm for Identifying Stellar Rotation in TESS Light Curves

Rae Holcomb
UC Irvine

We present a robust and automated algorithm to measure stellar rotation periods of stars observed by the Transiting Exoplanet Survey Satellite (TESS). Our approach uses the autocorrelation function (ACF) to identify periodicities ranging from 0.25 to 14 days among approximately 130,000 main-sequence stars observed by TESS with 2-minute cadence. We identify rotation periods for 13,467 stars, and demonstrate good agreement between our sample and known values from the literature, thus demonstrating the potential of this method for extracting stellar rotation periods from large datasets with minimal supervision. The resulting sample of fast-rotating stars provides a dataset that can be used as a basis for future gyrochronological studies, and, when combined with proper motions and distances from Gaia, to search for regions with high densities of young stars, thus identifying areas of recent star formation and undiscovered moving group members. Our algorithm will be publicly available on Github and is compatible with light curves from the TESS and Kepler missions.

The effect of small-scale magnetic fields on stellar convection and activity

Matthias Rempel
HAO/NCAR

The Sun is a unique star in the sense that we can observe it at high resolution and study phenomena at a detail that is hidden in stellar observations. This applies specifically to small-scale magnetic fields that are organized on the stellar surface on scale of granulation and smaller. Significant progress over the past 10-20 years in both solar observations and modeling through small-scale dynamo simulations point to a small-scale field of a large enough strength to have a dynamical impact on convection, differential rotation as well as large-scale magnetic activity. In this talk I will highlight lessons learned from the Sun that may have a broader impact on understanding stellar convection and magnetism.

Solar-cycle variations of internetwork magnetic fields

Marianne Faurobert
University of Nice, France

Small-scale magnetic fields in the quiet Sun contain in total more flux than active regions and represent an important reservoir of magnetic energy. But the origin and evolution of these fields still remain largely unknown. We present a study of the solar-cycle and center-to-limb variations of the magnetic-flux structures at small scales in the solar internetwork. We used Hinode SOT/Spectropolarimetric data from the irradiance program from 2008 to 2016 and applied a deconvolution to the Stokes profiles to correct them from the smearing due the Point Spread Function of the telescope. Then we performed a Fourier spectral analysis of the spatial fluctuations of the magnetic-flux density in 10"x10" internetwork regions spanning a wide range of latitudes. At low and mid latitudes and away from the active latitudes present at solar maximum, the power spectra do not vary significantly with the solar cycle. At high latitudes variations in opposition of phase with the solar cycle are observed at granular scales. Whatever the latitude the power of the magnetic fluctuations at scales smaller than 0.5" remain constant throughout the solar cycle. These results are in favor of a small-scale dynamo that operates in the internetwork.

Rotating Stars and the Mid-Frequency Continuum

Timothy Brown
Las Cumbres Observatory, CU/CASA

Spaceborne photometry enables the study of brightness fluctuations of Sun-like stars on timescales from minutes to years. There is however one range, spanning timescales between about an hour and a day (about 20 to 300 microHz) that has received little attention. In this range, almost all Sun-like stars show power-law continuous spectra, decreasing with frequency. Our study of about a hundred stars (mostly Pleiades members) shows the RMS variability in this band differs from star to star by factors of as much as 400, and depends mainly on the star's Rossby number. Its functional form is similar to that seen in several magnetism-related indices, including X-ray flux, horizontal magnetic field strength, and starspot area. We infer that the flickering in this "Mid-Frequency Continuum" (MFC) is connected with a magnetic process having time and spatial scales that are much smaller than those of global activity dynamos. The mechanism of the MFC's radiative signature is obscure. To address this issue at the lowest level (are the brightness elements more like spots, or plage?) we have obtained spectra of rapidly-rotating stars simultaneously with visits by TESS. I will report on these observations.

Formation of activity indicators in a 3D model atmosphere

Sneha Pandit
Rosseland Centre for Solar Physics, University of Oslo

The Sun, being the nearest star, can be used as a reference case for solar-like stars due to the availability of many spatio-temporally resolved solar spectra. There are several spectral lines that have been used as activity indicators for stars. Some of the strongest chromospheric diagnostics are the Ca II H & K lines which can be used to gauge the temperature stratification of the atmosphere as the line core and wings are formed in different regions of the solar atmosphere. The 1.5D radiation transfer code RH is used to obtain synthetic spectra from an enhanced network atmosphere simulated with the state-of-the-art Bifrost simulation. The activity indices generated from these lines could further be used to compare the stellar spectra of the sun-like stars with the solar spectra. These indices will provide insights into stellar atmospheres and their stratification. Meanwhile, ALMA provides the brightness temperatures which shed light on the activity and the thermal structure of stellar atmospheres. The global aim of the presented study is to establish more robust solar/stellar activity indicators using ALMA observations in comparison with classical diagnostics.

The Proxima Cen Campaign - A Multi-Wavelength Picture of Stellar Flaring

Meredith MacGregor
University of Colorado Boulder

At a distance of only 1.3 pc, Proxima Cen is the closest exoplanetary system orbiting an M-type flare star, making it a benchmark case to explore the properties and potential effects of stellar activity on exoplanet atmospheres. In April-July 2019, we observed Proxima Cen for roughly 40 hours with ground- and space-based facilities spanning the entire electromagnetic spectrum. Simultaneous data is available from the Australian Square Kilometre Array Pathfinder (ASKAP), the Atacama Large Millimeter/submillimeter Array (ALMA), the du Pont telescope at Las Campanas, the Las Cumbres Observatory Global Telescope (LCOGT), the Transiting Exoplanet Survey Satellite (TESS), the Hubble Space Telescope (HST), Swift, and Chandra. I will present the initial results of this survey, which are already challenging our understanding of flare mechanisms and energetics. For many detected flares, millimeter and FUV continuum emission trace each other closely while optical emission is delayed, suggesting that millimeter emission could serve as a better proxy for FUV emission from stellar flares and become a powerful new tool to constrain the high-energy radiation environment of exoplanets.

No Such Thing as a Simple Flare: Substructure and QPPs Revealed in 20 Second Cadence TESS Flares

Ward Howard
University of Colorado Boulder

We present the first statistical exploration of time-resolved substructure in large stellar flares from M-dwarfs with 20 second TESS data. A 20 second cadence TESS monitoring campaign of 226 low-mass flare stars during Cycle 3 recorded 3792 stellar flares and 440 events observed at high S/N. The survey discovered that degeneracies in flare morphology are often present at 2 minute cadence but can be resolved at 20 second cadence and quantified the debated occurrence rates of short-period pulsations in flares. For the first time, we resolve the rise phases to discover that rise phase complexity is very common. We then compare flare substructure against stellar rotation period. We also compare TESS flares with multi-wavelength observations spanning the X-ray to the millimeter. In particular, millimeter emission appears to be a common feature of M dwarf flares that remained undetected until now. Following the discovery of a large millimeter flare, a multi-wavelength program was executed involving ALMA, HST, and TESS to study the benchmark system Proxima Cen, the closest M dwarf flare star. Surprisingly, we find the UV and millimeter to trace each other closely, while associated TESS counterparts are not strongly correlated.

Mapping flare locations with time series observations of stellar ensembles

Ekaterina Ilin
Leibniz Institute for Astrophysics Potsdam / American Museum of Natural History

The amplification of magnetic fields inside the star, a process known as stellar dynamo, is driven by convection of the plasma within, and forces introduced by stellar (differential) rotation. The exact mechanisms behind the stellar dynamo are, however, poorly understood. One way to discriminate between different dynamo models is to map where magnetic fields emerge from the observationally inaccessible interior to the surface. These locations are highlighted by stellar flares – magnetically driven explosions in the corona, found in all stars with an outer convection zone. On the Sun (P_{rot}=25d), flares occur in a belt below 30° latitude around the equator, but recent findings suggest that flares occur much closer to the pole in rapidly rotating stars (P_{rot} <12h), implying a difference in the dynamo workings in the interior. In this talk, I will present a model we designed to infer the latitudes and longitudes of flaring regions in ensembles of rapidly rotating late M dwarfs from optical time series observations. I will show how our model allows us to map a 1D temporal flare distribution to the 2D physical map of the star, and show first results using light curves obtained with the Transiting Exoplanet Survey Satellite.

Recent observations of superflares on solar-type stars over various ages, and possible mass ejections

Yuta Notsu
CU Boulder / LASP / NSO / Tokyo Tech

Flares are frequent energetic explosions in the stellar atmosphere, and are thought to occur by impulsive releases of magnetic energy stored around starspots. Large flares (so called "superflares") generate strong high energy emissions and coronal mass ejections (CMEs), which can greatly affect the planetary environment and habitability. Recent Kepler photometric data have revealed the statistical properties of superflares on solar-type stars. Superflare stars are well characterized by the existence of large starspots on the surface, and their magnetic fluxes can explain well superflare energies. Flare frequency/energy depends on stellar rotation period. Young rapidly-rotating stars tend to have frequent superflares, while even slowly-rotating Sun-like old stars have superflares once every few thousand years. However, we still do not know how large CMEs are associated with superflares on these active stars. Then recently, these active superflare stars have been investigated in more detail thorugh recent multi-wavelength surveys. For example, we found blue-shifted H-alpha absorption profile during a superflare, which can give us hints on CMEs during superflares, and their effects on planets.

FRIDAY

The future of stellar rotation surveys

Jamie Tayar
University of Florida

Over the course of the week, we have heard about the evolution of rotation studies from a few solar-like stars in open clusters into a data-rich field covering a wide range of stellar masses and ages studied with a combination of very precise observations. In this talk, I will highlight some of the remaining open questions, including regimes where more data is needed. I will discuss some of the current and upcoming surveys that will help us collect this data, as well as highlight some possible connections to other related problems of stellar evolution, activity, and magnetism.

What Gaia Data Release 3 will bring to advance our understanding on evolution of rotation and magnetic braking in stars

Orlagh Creevey
Observatoire de la Cote d'Azur, Nice, France

Gaia Data Release 3 (GDR3, Q2 2022) will deliver a wealth of new insights on up to 1.8 billion objects in and around our Milky Way. GDR3 differs from any previous release because it now adds a new dimension to our existing knowledge: astrophysical characterization of its sources from analysis of mean and time-dependent spectral information (the BP, RP, and RVS spectra). The Third Gaia Data Release contains parameterization of between several million and several hundred millions of stars: temperatures, metallicities, masses, ages, rotational velocity, chromospheric activity index, rotational periods, variable star light curves and their characteristization, among many other data products. As the producers of these data, we propose to present an overview of the products from GDR3 of direct interest to the Skumanich relation community and how best to use them.

Building A Solar Analog Sample

Derek Buzasi
Florida Gulf Coast University

One valuable approach to studying rotation and activity focuses on the study of solar analogs or twins, stars which are like the Sun and thus might shed light on characteristics of its composition, structure, activity, planetary system, evolution, and future. Perhaps surprisingly, we still lack a large, coherent, consistent sample of solar analogs. Here I have used the K2 mission archive as an input to building such a sample, starting with approximately 2000 photometrically-selected analogs. K2 combines exquisite photometric precision, relatively long observing windows, and a selection of broadly distributed fields near the ecliptic plane. For each candidate, I measured photometric activity levels and rotation periods using K2 light curves, distances and improved colors using Gaia, and chromospheric/coronal activity diagnostics with Chandra and GALEX. The best candidates were selected for follow-up with the APO 3.5-meter ARCES instrument to determine metallicities and consistent estimates of RHK' indices. The result is a new sample of well-characterized analogs with $V < 10$, distributed roughly uniformly near the ecliptic plane.

Study the tortoise, not just the hare

Philip Judge
High Altitude Observatory

Darwin encountered enormous Galapagos tortoises in 1835 around the time that Schwabe was collecting sunspot numbers. The creatures were slow and easy to study. Of course, fauna from the Galapagos played a central role in our understanding of evolution of life; genetic records imprinted in modern animals have since given us pages in the book of life history. Skumanich's 1972 work represents the first 3 pages in the book of stellar magnetic evolution, studying (like Darwin) only what was observable at a given time. The Sun and stars continue to be studied by politically palatable 1-10 year long missions, measuring short duration phenomena – analogous to the peculiar springtime "boxing" of the March Hare. Stellar activity measurements over multiple decades (sampling sun-like cycling) are now a part of history, just as their need from space weather, dynamo theory, exoplanet habitability seems greater than ever. The communities must support tortoise-like measurements of stellar chromospheric signatures, extending the record begun in 1965, and used by Andy in 1972. A "palatable path" might be through development of automated observatories at under-privileged colleges, I present some ideas along these lines.

The early spectropolarimetric inversions

Valentin Martinez Pillet
National Solar Observatory

In the late 80's A. Skumanich played a leading role in advancing our understanding of radiative transfer processes in stellar atmospheres in the presence of a magnetic field. Of his multiple contributions, developing robust inferences of the vector magnetic field estimates on the sun from spectropolarimetric observations were particularly important. It demonstrated how consistent and reliable vector magnetic field estimates could be obtained limited only by noise in the data. Andy's links with the international community that develop the theory of polarized radiative transfer were vital. In the early 90's, the Advanced Stokes Polarimeter (ASP) demonstrated from a practical standpoint the relevance of the theoretical developments in which Andy participated. The ASP convinced the solar community that reliable vector magnetic field measurements are possible. This significant achievement paved the way for proposing a facility equipped with four spectro-polarimeters —the Daniel K Inouye Solar Telescope— to the community.

Nice memories from a collaboration on sunspots

Jose Carlos del Toro Iniesta
IAA-CSIC

Back in 1994, when I still was at the IAC, I had the idea of using the (by then) new SIR inversion code to a full vector spectropolarimetric map of a sunspot as obtained with the HAO's Advanced Stokes Polarimeter. The opportunity was open to study the three-dimensional structure of sunspots from a semi-empirical basis. A collaboration between HAO and IAC had already started a few years earlier with the stays in HAO of Jorge Sánchez Almeida and Valentín Martínez Pillet (today's NSO director) as postdocs. Direct contact with the champions of ASP, Andy and Bruce, Bruce and Andy, was hence granted and I readily suggested them to undertake the study with their data and our code in the frame of the PhD thesis of a new student of mine, Carlos Westendorp Plaza. A few years later (1997), the discovery that penumbral material comes back to the solar interior at the external penumbral border was published in the Nature journal. The paper was followed by a series in ApJ on an optical tomography of a sunspot. The friendly and enriching discussions with Andy and Bruce remain as one of the most rewarding experiences in my (already long) career.

Skumanich-55 revisited

Axel Brandenburg
Nordita

When I started my undergraduate research in Hamburg in 1984, my professor pointed me to Skumanich-55. It is interesting to review the thinking at the time. The Vitense-53 paper laid the foundation for thinking that the Schwarzschild-unstable layer was at least 70 Mm deep, contrary to the earlier picture of the 1930s of less than 1 Mm. In Skumanich-55, the governing idea is not to postulate a characteristic size of eddies, but to ask which eddies grow the fastest. In unstratified Rayleigh-Benard convection, they all grow at the same rate, but in a polytropic layer, smaller eddies are more unstable, which led Skumanich to argue that small eddies should be predominant. This is different from standard mixing length ideas and perhaps also from some simulations. However, both ignore the phenomenon of entropy rain and the possibility of the convective flux in the deeper layers not being carried by a gradient flux, but predominantly by the Deardorff flux. Although none of this was part of the Skumanich model, it also suggests a predominance of smaller eddies. In this sense, his model deserves some renewed attention!

POSTERS

TESS-Gaia synergy: automating rotation measurements for new Hyades stellar stream members

Oliver Hall
European Space Research and Technology Centre - ESA ESTEC

Tidal tails of stellar clusters are important laboratories for the evolution of stellar populations and the Milky Way at large. Recent data from the Gaia mission has allowed identification of new tidal tail structures thanks to its high-precision astrometric data. One such tidal tail belongs to the Hyades, recently detected by Jerabkova et al. (2021). However, Gaia data alone is not enough to robustly confirm tail membership. In this work, we aim to confirm the coeval status of stars in the newly identified Hyades tidal tail through the use of gyrochronology, which infers stellar ages from their rotation rates.

Exploring Millimeter Indicators of Solar-Stellar Activity

Atul Mohan
RoCS, ITA, University of Oslo

Stellar activity is closely linked to the plasma dynamics across its atmospheric layers. The continuum emission at different frequencies in the mm - cm range (∼10 - 1000 GHz) forms at different heights in the stellar atmospheres, letting us probe the brightness temperature (TB) variations across the chromosphere to corona. The emission at ∼50 -1000 GHz being mainly thermal, provides the vertical temperature structure, while below 50 GHz, the gyrosynchrotron emission could tell us about the magnetic fields. In a recent study, we compiled a database of main sequence stars detected with ALMA. The 10 -1000 GHz spectra of these stars were gathered and compared with model spectra calculated with the PHOENIX code. We found that the stars with photospheric effective temperatures, Teff ∼3000 - 7000 K show a rise in TB with decreasing frequency, suggesting the presence of hot chromospheres. Interestingly, the TB spectral steepening was found to be higher for cooler (Teff), fast rotating and hence more active stars in the sample which also included the Sun-as-a-star. Despite the small sample size, this initial result demonstrates the power of mm - cm TB spectrum to characterise stellar atmospheric structure and there by its activity.

Starspot Coverage and the Temperature-Dependent Radius Dispersion of Low-Mass Stars

Michele Silverstein
NASA Goddard Space Flight Center

Radius inflation of red dwarf stars can be attributed to multiple factors. Young stars that have not quite contracted onto the main sequence are puffier than their main sequence counterparts. Unresolved binaries can appear to be single stars with large radii, and rapid rotation can inflate stars. In low-mass main sequence stars, the dispersion in stellar radius also changes as function of effective temperature; here we examine the role of magnetic activity in the form of starspot coverage on this radius spread for stars from M0V to the end of the main sequence. We proceed as following: (1) We use publicly available software to identify starspots and determine spot coverage in time series photometry from, e.g., ASAS-SN and TESS. (2) We derive effective temperature and stellar radius using multiple methods, including an SED method that matches long baseline interferometry radii to within 6%. (3) We populate the radius vs. effective temperature vs. spot coverage diagram and compare to the Somers et al. 2021 models. With this program we move closer to disentangling the relationship between stellar radius and magnetic activity across the full range of red dwarf masses, using the most recently developed models, software, and data.

Effective Rossby numbers of stellar convective envelopes from 3D simulations

Regner Trampedach
Space Science Institute

The Rossby number, the ratio of inertial to Coriolis forces, of convective envelopes is a deciding parameter in the magnetic braking formulation of van Saders et al. (2016) and Metcalfe et al. (2016). What is needed is a bulk quantity, but the Rossby number is inherently a local quantity, since those forces depend on location in the star. Using results from the grid of 3D convection simulations by Trampedach et al. (2013) the convective velocity scales and convection zone depths are calibrated for 1D stellar envelope models carefully matched to each simulation. This velocity structure is then used for a volume integration of the Rossby number modulo a rigid body rotation rate. The results will be compared to the current standard choice, which is somewhat arbitrary.