1. A spin-down clock for cool stars from observations of a 2.5-billion-year-old cluster

Its difficult to determine the age of low mass (cool) stars using traditional dating methods as either they change very little as they age or are hard to measure. As stars age the rate of rotation decreases steadily as they lose their angular momenta – can be used to determine age gyrochronology. Need to understand the relation between rotation rate and age, this has been done for stars less than one-billion years, for older stars this has been inferred from model predictions.

For young cool stars (< 300 million years) they typically begin their main sequence phase with a dispersion in their rotation period P, generally between 0.1-10d. This dispersion decreases rapidly with time as they lose angular momentum through magnetically channelled winds. This causes the period to increase and converge towards a well-defined relationship with mass by the age of 600Myr. Observations suggest that stars older than 600Myr occupy a single surface P = P(t,M) in P-t-M space. Where the photometric colour of the star is a proxy for the mass.

The gyrochronology age of a cool star is derived under the assumption that its rotational evolution has not been influenced by external forces

Rotation rate is measured from small periodic fluctuations in the measured brightness of a star as star-spots reduce the amount of light a star gives off. Older stars have fewer and smaller spots, thus their period is harder to detect.

https://www.cliffsnotes.com/study-guides/astronomy/observational-properties-of-stars/proper-motions-and-radial-velocities

Radial velocity is determined from the Doppler effect in the spectra of the stars. ...

Proper motion is the rate of angular drift across the sky (measured in arc seconds

2. Weakend magnetic braking as the origin of anomalously rapid rotation in old field stars.

There are two approaches to gyrochronology

- Purely empiricial: use a sample of stars with already known ages and rotation periods to construct a period-age relationship
    - Generally simple power las in age, period and some mass dependant quantity (widely used) (I think this is what we will be doing). The current empirical place (based on the sun I think) doesn't do a brilliant job.
- Model based approach: uses stellar models and a prescription for the magnetic braking to account for the functional dependence on all the relevant quantities, relies on calibrators to determine the loss in angular momenta. [Focus of the paper I think]

The Skumanich relation yields that the loss of angular momentum is proportional to the cube of the angular rotation velocity $\left(\frac{dJ}{dt} \propto \omega^3\right)$. There is a constant of proportionality called the Rossby number which is often used ($R_0 = P/\tau_{cz}$), where τ is the convective overturn (typical **timescale** for a **convective** cell to rise in a gas). This Rossby number is often used to parameterise the magnetic field strength, the mass and the composition dependence to the spin down(spin down: lose angular momenta), observed saturation of the magnetic braking in rapid rotators and the sharp transition to rapid rotation in hot stars (>6250K) due to thinning convective envelopes.

Previous work found that the sample studied did not obey a simple power-law period-age relation. However, they did not take into account several quantities: metallicity, changes in the stellar moment of inertia. They also used a sample did not have detailed seismic modelling or spectroscopy, thus biasing the seismic ages.

To address the limitations of previous work, they only utilised stars with high precision ages, detailed astroseismic modelling, measured rotation periods and known metallicities (21 stars). They found that: Young stars generally lie on the plane where expected, but intermediate and older stars rotate more rapidly than expected.

The data they studied did not fit neither the empirical or theoretical modes(with chi-squareds of 155.6 and 54.9). They found a systematic offset towards short rotation periods, concluding that this because the models over predict the angular momentum loss, therefore magnetic braking is weaker in intermediate and old stars.

They adapt the model to (in addition to the Rossby scaling) include that the effective angular momentum loss ceases above a critical Rossby threshold. Above this threshold angular momentum is conserved, the critical value was varied to determine what is most appropriate. This keeps the behaviour the same for younger stars(where R0 is small due to the rapid rotation), but limits the expected loss of angular momentum in older stars.

The equation used to determine the loss of angular momenta taking into taccount the critical Rossby factor is given on page 12

Hotter heavier stars reach the Rossby threshold at younger ages, therefore see discrepancies between the fiducial gyrochonology relationships and the observations at earlier times in the panels of increasing ZAMS T_{eff}.

(ZAMS T_{eff}) zero age main sequence effective temperature.