# *Clusters and Stellar Angular Momentum Evolution*

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## TWO GOALS

### THE ROTATION-MASS-AGE RELATIONSHIP

•Rotation periods can be inferred for spotted late-type stars.

•~13% of MS field stars are variable at the 1% level, with strong mass trends (Hartman et al. 2009, astro-ph/0907.2924)

•Ground and space based planet transit searches (such as KEPLER and COROT) will therefore produce enormous databases of stellar rotation periods

•Rotation is a potential age diagnostic because stars spin down as they age. We therefore have the prospect of reliable age estimates for bulk field populations *provided that rotation-mass-age relationships can be properly calibrated.*

•*Open cluster data is uniquely capable of doing this.*

### UNDERSTANDING ANGULAR MOMENTUM EVOLUTION

•Rotation studies can also inform us about fundamental questions in stellar structure and evolution:

•The rotation rates of stars are set during the star and planet formation process. There is valuable information encoded in the initial angular momenta of stars.

•Late-type stars lose angular momentum in magnetized winds. Observed trends in loss rates with mass can inform dynamo theories and test mechanisms for chromospheric and coronal heating.

•Angular momentum transport and mixing in radiative regions is an unsolved problem with potentially broad astrophysical consequences.

## THE STANDARD MODEL

### INITIAL CONDITIONS

•T Tauri stars provide initial rotation data. Star-disk interactions (Shu et al. 1994) can transfer angular momentu from contracting protostars to their accretion disks. Models which convolve the T Tauri distribution with a range of disk coupling timescales can successfully reproduce the inferred time evolution of rotation for low mass stars

### ANGULAR MOMENTUM LOSS

• Theory predicts a loss rate that scales as $\omega^3$ for slow rotation (Weber & Davis 1967); above a saturation threshold $\omega_{crit}$ the loss rate scales linearly with $\omega$.

•*Stars will thus lose their memory of the initial conditions (rapid rotators spin down faster than slow ones), and once this has occurred rotation is predicted by age.*

•Chromospheric and coronal diagnostics become insensitive to rotation above a critical threshold (Krishnamurthi et al. 1998), and a saturation in the loss rate is required to explain the survival of rapid rotation in young open cluster stars.

•The saturation threshold is mass dependent, and saturation delays the epoch where rotation is a useful age indicator (Sills et al. 2000).

### ANGULAR MOMENTUM TRANSPORT

•Hydrodynamic mechanisms, waves, and magnetic fields can all couple the radiative core to the convective envelope for angular momentum purposes.

•The observed spindown pattern places strong constraints on the timescale for coupling, and rule out some popular models which predict strong coupling.

## ABSTRACT

The origin and evolution of stellar rotation has proven to be both important and challenging. Data obtained in star clusters has already provided key constraints on the role of protostellar disks and the timescales for angular momentum loss and internal transport. Recent data sets also provide empirical support for the idea that a wide range of rotation rates converge on the main sequence. We evaluate the prospects for rotation-mass-age relationships and the role of open clusters in calibrating them.

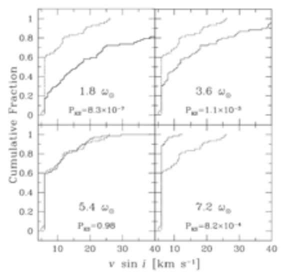


**Figure 1.** Cumulative v sini distributions for Pleiades data projected to the age of the Hyades (solid lines) compared to actual Hyades data (dotted lines) for different loss rate saturation thresholds. Consistency between the two cluster data sets places strict bounds on the allowed torque (4.5 $\omega_{sun} < \omega_{crit} < 6.5\ \omega_{sun}$ for $P_{ks} > 10\%$). From Tinker et al. 2002.

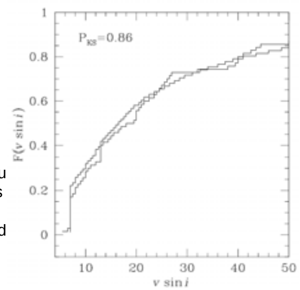


**Figure 2.** Cumulative v sini distributions for ONC data projected to the age of the Pleiades (thick line) compared to actual Pleiades data (thin line) for a model with $\omega_{crit} = 5.4\ \omega_{sun}$ and a flat distribution of disk coupling timescales from 0-6 Myr. From Tinker et al. 2002.

## A CONSISTENT PICTURE FOR LOW MASS STARS

Tinker, Pinsonneault & Terndrup 2002

•Focus on stars below 0.5 solar masses (deep surface CZ or fully convective), where core-envelope coupling is not an important effect.

•Take rotation data from the ONC, convolve it with a flat distribution of disk lifetimes from 0-6 Myr, and evolve it forward to the age of the Pleiades.

•Reproducing the rapid rotator population places strong empirical constraints on the saturation threshold for angular momentum loss (Figure 1).

•Models which are consistent with the ONC-Pleiades system are consistent with the data in the older Hyades system (Figure 2).

•*We can therefore self-consistently reproduce the time evolution of rotation in the lowest mass stars.*

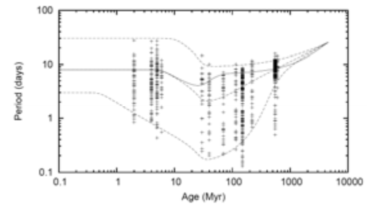


**Figure 4.** Solid body spindown models (dashed lines) compared with one with a coupling timescale of 100 Myr (solid line) and with a compilation of open cluster rotation data (crosses). The excess of long period systems above the middle dashed line, and the inconsistency in their fraction within the young open clusters, is evidence against SB models.

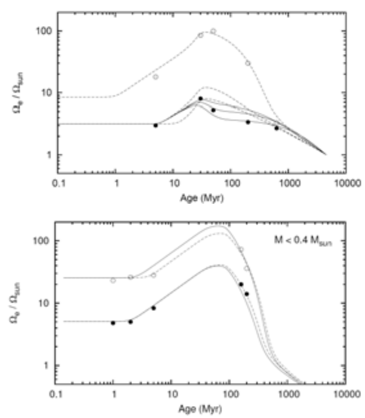


**Figure 5.** Upper 90[th] and lower 25[th] percentiles of the open cluster data for 0.9-1.1 solar mass stars compared with models with different coupling timescales (dashed=SB, solid 25, 50, 100 Myr from top to bottom). Low mass data (bottom panel) is consistent with solid body spindown, indicating that a problem with the loss or initial conditions model is not responsible

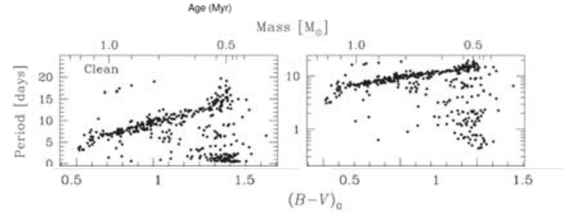


**Figure 3.** Period distribution for the clean sample of M37 stars from Hartman et al. 2009 on a linear (left) and logarithmic (right) scale.

## CONVERGENCE SEEN IN M37

•Hartman et al. 2009 obtained a large rotation period data set in M37 during the course of a planet transit search (Figure 3).

•.For solar-type stars the predicted convergence of rotation rates appears to be present in the data, a conclusion also consistent with more limited earlier data in the Hyades. *The basic hypothesis of a rotation-age relationship is therefore supported for them.*

•The late-type stars in the cluster illustrate the problem of rotation-age relationships in stars which have not yet lost memory of their initial conditions. *In the field we would not be able to assign these stars to a sequence and would predict a large age spread in what is known to be a coeval sample.*

•In addition to probable synchronized binaries (P < 5d) there is a population of slowly rotating stars. If confirmed as members these would require a very different model of angular momentum evolution which had a range of internal rotation rates even at late ages.

## TIMESCALE FOR CORE-ENVELOPE COUPLING

•There are popular models of angular momentum transport which invoke strong magnetic coupling (e.g. Spruit 2002). When applied to open cluster stars they predict extremely rapid core-envelope coupling, and thus that stars should spin down as solid bodies.

•A number of investigators have studied the spin down of young open clusters and derived coupling timescales of 20-100 Myr (Keppens et al. 1995; Krishnamurthi et al. 1998; Allain 1998; Irwin et al. 2007). We derive coupling timescales ~50 Myr consistent with earlier measurements (Figures 4 and 5).

•The hypothesis of strong magnetic coupling of radiative cores with convective envelopes is thus not consistent with the data.

•As predicted by theory, rapid rotators are also more strongly coupled than slow rotators. We also find that the timescale is mass dependent. A proper model therefore needs more than a constant timescale for all masses to account for the data.

•Rotation-mass-age relationships which neglect this effect will produce spuriously old ages for stars.

## A CAUTION ON SYSTEMATICS IN PERIOD SAMPLES: THE PLEIADES

• Rotation period distributions, unlike v sini measurements, are not subject to inclination effects. However, there are strong selection effects related to aliases and detectability.

•The Pleiades cluster has both v sini and Prot data, and we can test their internal consistency by convolving the latter with a random distribution of sin i and radii predicted by interiors theory.

•The cumulative rotation period data is *not* consistent with the v sini distribution; slow rotators, which are more difficult to detect, are under-represented.

## CRITICAL AREA FOR FUTURE WORK

•Data in ~5-10 Myr old systems will be the most powerful diagnostic of protostar-disk coupling.

•Data in open clusters younger than the Pleiades (30-100 Myr) will place strong constraints on internal angular momentum transport.

•There is an almost complete lack of rotation data in clusters older than ~625 Myr (and virtually all field star data lack independent age estimates). *Rotation-age-mass relationships therefore rely almost completely on extrapolations calibrated on the Sun, and there is a critical need for direct measurements in clusters as a function of mass.*

•The open cluster age scale is a major source of uncertainty, and many differences in published results can be traced to different assumed age scales.

•Theoretical models need to incorporate both core-envelope decoupling and a range of initial rotation rates in order to define the bounds of applicability of rotation-age-mass relationships.