

Rotation and activity in the solar-type stars of NGC 2547

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Accepted 2000 April 14. Received 2000 April 14; in original form 2000 February 11

ABSTRACT

We present high-resolution spectroscopy of a sample of 24 solar-type stars in the young (15–40 Myr), open cluster NGC 2547. We use our spectra to confirm cluster membership in 23 of these stars, to determine projected equatorial velocities and chromospheric activity, and to search for the presence of accretion discs. We find examples of both fast ($v_e \sin i > 50 \text{ km s}^{-1}$) and slow ($v_e \sin i < 10 \text{ km s}^{-1}$) rotators, but no evidence for active accretion in any of the sample. The distribution of projected rotation velocities is indistinguishable from the slightly older IC 2391 and IC 2602 clusters, implying similar initial angular momentum distributions and circumstellar disc lifetimes. The presence of very slow rotators indicates either that long (10–40 Myr) disc lifetimes or internal differential rotation are needed, or that NGC 2547 (and IC 2391/2602) were born with more slowly rotating stars than are presently seen in even younger clusters and associations. The solar-type stars in NGC 2547 follow a similar rotation–activity relationship to that seen in older clusters. X-ray activity increases until a saturation level is reached for $v_e \sin i > 15\text{--}20 \text{ km s}^{-1}$. We are unable to explain why this saturation level, of $\log(L_x/L_{\text{bol}}) \approx -3.3$, is a factor of 2 lower than in other clusters, but rule out anomalously slow rotation rates or uncertainties in X-ray flux calculations.

Key words: stars: activity – stars: late-type – stars: rotation – open clusters and associations: individual: NGC 2547 – X-rays: stars.

1 INTRODUCTION

Open clusters are obvious laboratories in which to study the evolution of stellar X-ray activity. They contain stars with a variety of masses but a similar age, distance and composition. A large amount of *Einstein*, and *ROSAT* X-ray observatory time was spent looking at open clusters (see, e.g., the reviews by Randich 1997 and Jeffries 1999), and a major achievement of these missions was to show that solar analogues, and stars of even lower mass, in young open clusters could have X-ray activity orders of magnitude greater than the Sun. This activity correlates with fast rotation, and is hypothesized to be due to an internal convective dynamo which generates the magnetic fields that both heat and confine hot coronae. The evolution of X-ray activity is thought to obey an age–rotation–activity paradigm (ARAP). Young single stars are rapidly rotating and active, but lose angular momentum and spin-down as they age, resulting in a decrease of their X-ray activity.

The spin-down of cool stars as they age is not as simple as the $\Omega \propto t^{-1/2}$ law once proposed by Skumanich (1972). It appears that G and K stars arrive on the main sequence (for instance, in the Pleiades – age ≈ 100 Myr) with a spread in rotation rates from a few times to a hundred times the solar rotation rate. Subsequently, this spread almost converges by the age (600 Myr)

of the Hyades. In recent times these phenomena have been understood in terms of braking caused by a magnetically coupled, ionized wind, discussed in detail by (for instance) Barnes & Sofia (1996) and Krishnamurthi et al. (1997). The spread in rotation rates observed at the ZAMS, combined with the magnitude and rather narrow distribution of rotation rates among pre-main-sequence (PMS) stars, implies that, in order to produce the fastest ZAMS rotators, substantial angular momentum must be lost during the PMS phase, and the wind braking mechanism must saturate at high rotation rates (Bouvier, Forestini & Allain 1997a). This could be due to a saturation of the dynamo mechanism itself, or perhaps changes in the magnetic field geometry (Barnes & Sofia 1996).

It has long been supposed that during the initial stages of PMS rotation evolution, wind braking was negligible compared with the moment of inertia decrease as a star contracts towards the ZAMS. An alternative angular momentum loss mechanism is required, and might be provided by magnetic torques transferring angular momentum to a circumstellar disc (Königl 1991; Shu et al. 1994). It can be shown that disc-regulated angular momentum loss leads to almost constant angular velocity as a PMS star shrinks. A range of disc lifetimes, perhaps connected to the initial disc mass (Armitage & Clarke 1996), then results in stars becoming decoupled from their discs at varying ages. Spin-up from this

point to the ZAMS, combined with wind angular momentum loss that saturates above some threshold rotation rate, can provide a very wide spread of ZAMS rotation rates. This scenario has been modelled extensively by Collier-Cameron, Campbell & Quaintrell (1995), Keppens, MacGregor & Charbonneau (1995), Bouvier et al. (1997a) and Krishnamurthi et al. (1997).

Support for disc-regulated PMS angular momentum loss comes from observations that show a connection between rotation rates in PMS stars and the presence of circumstellar accretion discs. Choi & Herbst (1996, and references therein) claimed that rotation rates in the Orion nebula cluster were bimodal, with periods either shorter or longer than 4–5 days. They proposed that the slower group of rotators might be those that still maintained a circumstellar accretion disc. Bouvier et al. (1993) showed that in their sample of Taurus-Auriga PMS stars, the classical T Tauri stars (CTTS – those stars showing optical signatures of active accretion and circumstellar discs) rotated more slowly on average than the weak T Tauri stars (WTTS) that showed no sign of circumstellar discs. Furthermore, Edwards et al. (1993) were able to show that a similar situation held when the near-infrared signatures of discs were considered for Orion PMS stars. More recently, the whole disc-regulated angular momentum loss idea has been challenged by Stassun et al. (1999), who find little correlation between disc signatures and rotation rates in a larger sample of low-mass (0.2–0.6 M_{\odot}) Orion PMS stars, as well as a population of extremely rapid rotators (periods <2 d) both with and without discs. They claim that an alternative to disc-locking is required, if the Orion rotation rate distribution is to evolve into that seen among the ZAMS stars of the Pleiades cluster.

These new ideas on the evolution of stellar rotation rate have been successfully applied to X-ray observations of young clusters of stars (e.g., IC 2391 and IC 2602, age \approx 30 Myr – Stauffer et al. 1997, hereafter S97; Alpha Per, age \approx 60 Myr – Randich et al. 1996; Pleiades, age \approx 100 Myr – Stauffer et al. 1994). In every cluster studied so far the ARAP appears to hold, with rotation providing the parameter that determines the level of X-ray emission from a star. This was most clearly demonstrated in the Pleiades by Stauffer et al. (1994). They showed that X-ray activity (measured by L_x/L_{bol}) in solar-type stars increases with $v_e \sin i$ until a saturation is reached at $L_x/L_{\text{bol}} \approx 10^{-3}$ for $v_e \sin i > 15\text{--}20 \text{ km s}^{-1}$, with perhaps a decrease in the $v_e \sin i$ threshold for lower mass stars with thicker convection zones (Krishnamurthi et al. 1998). This relationship has since been confirmed in the younger Alpha Per and IC 2391/2602 clusters, with some hint that the X-ray activity may even decline at ultrafast rotation rates ($v_e \sin i > 100 \text{ km s}^{-1}$; Randich 1998).

NGC 2547 is an excellent cluster for exploring some of these issues. Jeffries & Tolley (1998, hereafter JT98) reported X-ray observations of the cluster, detecting a rich population of PMS stars with an age, deduced from fits to low-mass isochrones, of (14 ± 4) Myr – somewhat younger than IC 2391/2602. In order to produce the large numbers (\sim 85 per cent with $v_e \sin i < 20 \text{ km s}^{-1}$) of slow rotators at the age of the Pleiades, the solid-body rotation models of Bouvier et al. (1997a) predict that at \sim 15 Myr about 15–20 per cent of solar-type stars should still possess circumstellar discs, and that approximately 50 per cent of stars should have a projected equatorial velocity ($v_e \sin i$) less than 20 km s^{-1} . Shorter disc lifetimes are allowed if differential rotation between the core and convective envelope is possible (Keppens et al. 1995; Krishnamurthi et al. 1997), and would be more in accord with the (few) available measurements in T Tauri stars, which suggest median and maximum disc lifetimes of about

1–3 Myr and \sim 10 Myr respectively (Strom et al. 1989; Skrutskie et al. 1990; Edwards et al. 1993; Kenyon & Hartmann 1995).

We would therefore expect (according to the ARAP) that approximately half of the solar-type stars in NGC 2547 should show saturated X-ray emission. In fact, the distribution of X-ray emission in NGC 2547 does not meet these expectations. Fig. 1 compares L_x/L_{bol} as a function of intrinsic colour for NGC 2547 with that of IC 2391/2602 members (taken from Randich et al. 1995, Patten & Simon 1996, S97 and Simon & Patten 1998). The X-ray activity appears to peak or saturate in NGC 2547 at a level about a factor of 2 lower than in IC 2391/2602 for the late F to early K stars. The same is true when NGC 2547 is compared with the Alpha Per and Pleiades clusters (see also fig. 6 in Randich et al. 1995 and fig. 13 in JT98). JT98 argued that this was not a simple scaling error in the conversion from X-ray count rates to X-ray fluxes in NGC 2547, because cooler stars [$(B - V)_0 > 1.3$, $(V - I)_0 > 1.8$] appear to have a saturation level, $L_x/L_{\text{bol}} \approx 10^{-3}$, that is consistent with other clusters. They suggested that perhaps *all* the solar-type stars in NGC 2547 were rotating more slowly than a speed of 20 km s^{-1} , above which the X-ray emission of solar-type stars in other clusters appears to saturate. This might be the case if the stars in NGC 2547 had either started life with much less angular momentum than stars in other clusters, or had somehow retained circumstellar accretion discs for longer than usual.

The possibility that disc lifetimes could exceed 10 Myr in some circumstances would have important implications for stellar angular momentum loss and the possible formation of planetary systems. In this paper we present the results of high-resolution spectroscopy of a sample of solar-type stars in NGC 2547. Our aim is to test for the presence of active accretion discs, to measure rotation rates, and to see whether the ARAP can successfully explain the X-ray emission that is seen in these stars. In Section 2 we outline the sample of stars we have observed, the observations that were made, and their analysis. Section 3 presents the results of these analysis, and compares the rotation and activity in NGC 2547 with that in other young clusters. These results are discussed in Section 4.

2 OBSERVATIONS

2.1 Sample selection

All of our targets were selected as optical counterparts to X-ray sources by JT98. They have $B - V$ and $V - I_c$ colours and V magnitudes that are consistent with membership of the NGC 2547 cluster. For the remainder of this paper we assume that the intrinsic distance modulus to the cluster is 8.1 ± 0.1 , and that the reddening is given by $E(B - V) = 0.06$ or $E(V - I_c) = 0.077$ (see JT98). An earlier photoelectric study of early-type members by Clariá (1982) has established that any differential reddening in the cluster is less than 0.02 (rms). JT98 fitted isochrones to the X-ray sources in NGC 2547 and found an age of 14 ± 4 Myr, compared to about 25 Myr for IC 2391 and IC 2602 using the same isochrones and colour- T_{eff} relationship. There is some evidence that these isochronal ages may be underestimates (see Section 4.1).

Fig. 1 shows the distribution of X-ray activity in NGC 2547 as a function of intrinsic colour. The approximate sensitivity threshold for detecting X-ray sources in the cluster is shown as a dotted line. This threshold was determined by JT98 and is appropriate for cluster members situated near the centre of the *ROSAT* field of view. For objects nearer the edge of the *ROSAT* field of view, the

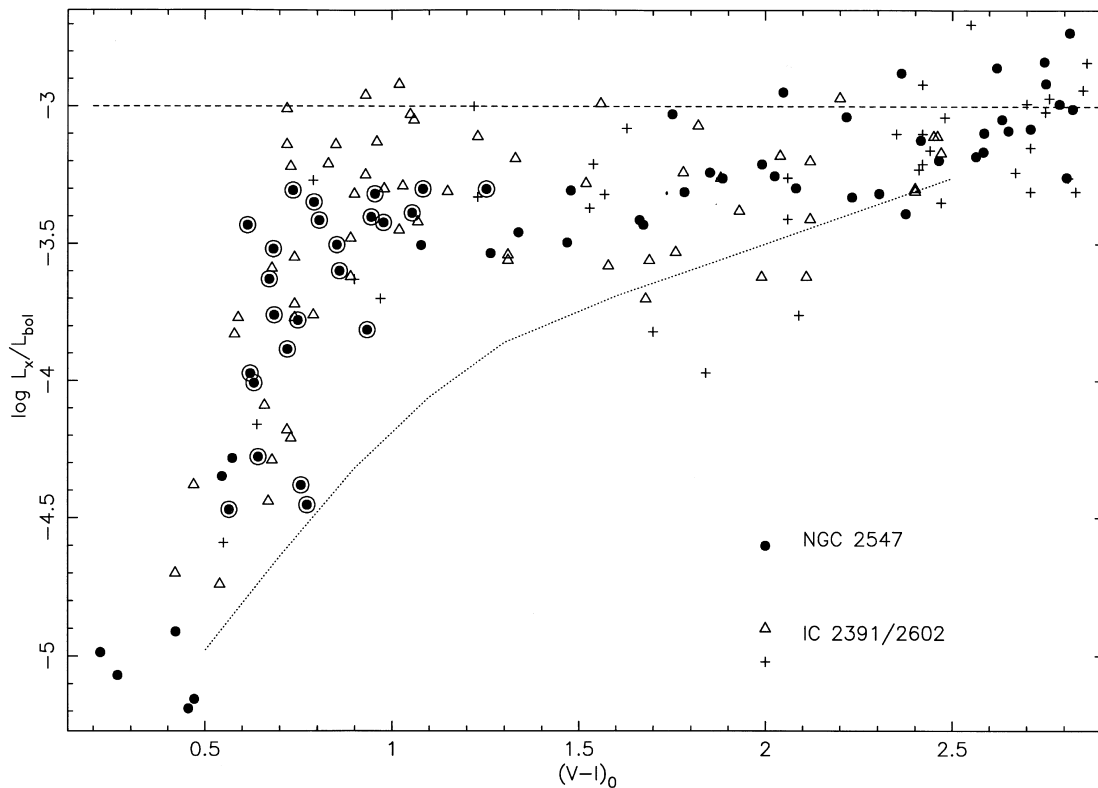


Figure 1. X-ray activity, expressed as L_x/L_{bol} , in NGC 2547 (dots) as a function of intrinsic colour, compared with stars in IC 2391/2602 (triangles and crosses). The dotted line indicates the X-ray sensitivity limit for NGC 2547, and the dashed line indicates the ‘saturation level’ for X-ray emission reached in all young clusters. The circled NGC 2547 points were selected for high-resolution optical spectroscopy in this paper. Triangles represent members of IC 2391/2602 confirmed by spectroscopy in S97. Crosses are X-ray-selected members of IC 2391/2602 so far unconfirmed by spectroscopy.

detection threshold is approximately 0.3 dex higher. The argument used by JT98, which we shall also use here, is that an X-ray-selected sample of cluster members would normally be biased towards faster rotators; however, if the X-ray sensitivity threshold is low enough that there are no cluster members situated at or slightly above this threshold, then it is most likely that the X-ray-selected sample is complete. This might not be true if X-ray luminosity functions showed a bimodal distribution, but this is not the case in the solar-type stars of the Pleiades and Hyades, where complete optical samples have been observed at X-ray wavelengths (Stern et al. 1992; Stauffer et al. 1994).

If we now consider just the stars in NGC 2547 with $0.8 < (V - I_c)_0 < 1.40$ (corresponding roughly to masses $1.0 > M > 0.8 M_{\odot}$ according to the D’Antona & Mazzitelli 1997 isochrones used to determine the age), there does seem to be a significant gap between the X-ray sensitivity threshold and the lowest activity levels detected, indicating that the X-ray-selected sample of solar-type stars should be almost complete. The same may not be true for hotter and cooler stars, where it is still possible that some slow rotators have not been seen in X-rays. The number of X-ray-selected solar-type stars found in the cluster *is* consistent with the number of higher mass stars and canonical initial mass functions (see JT98 for details). However, the uncertainties in these numbers are too large to place any strong constraints on the sample completeness.

The stars we have observed spectroscopically are indicated by the circled points in Fig. 1. The colours and magnitudes of these stars are listed in Table 1, where we adopt the identifiers and data from JT98. Some of these stars lie significantly above the single

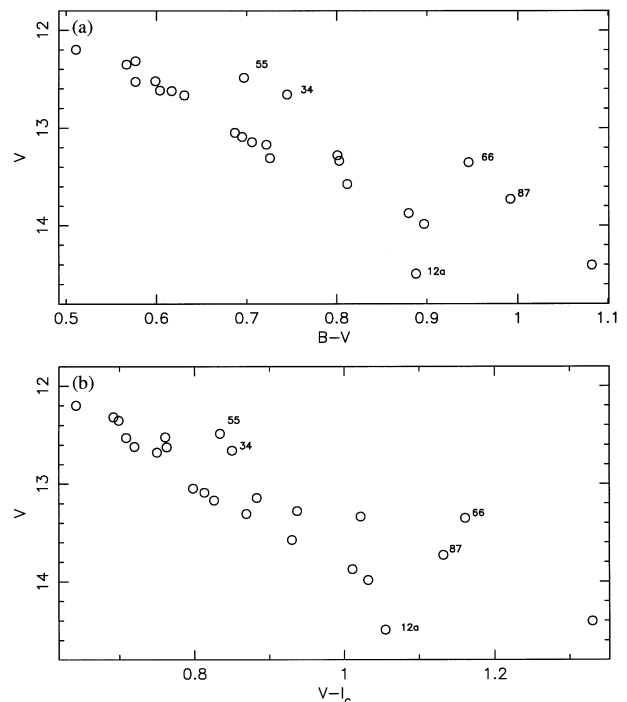


Figure 2. Colour–magnitude diagrams for the sample of stars chosen for high-resolution spectroscopy in NGC 2547. A number of stars referred to in Section 2.3 are labelled. (a) V versus $B - V$. (b) V versus $V - I_c$.

Table 1. Spectroscopy in NGC 2547. Identifiers and photometry are from JT98. Columns 5 and 6 give heliocentric RVs and $v_e \sin i$. Column 7 gives the EW of the H α line and column 8 lists the L_x/L_{bol} from JT98.

ID	V	B - V	V - I _c	RV (km s ⁻¹)	$v_e \sin i$	H α EW (Å)	Log(L_x/L_{bol})	Notes
RX3	14.403	1.082	1.330	+13.4 ± 0.8	18.8	+0.5	-3.30	
RX10	13.984	0.897	1.032	+13.3 ± 0.7	20.1	-0.2	-3.32	
RX12a	14.492	0.888	1.055	+29.3 ± 0.5	35.5	0.0	-3.42	
RX12a				+27.1 ± 1.1	35.5	0.0		2
RX16	12.199	0.511	0.642	+12.8 ± 0.6	7.7	-1.4	-4.47	
RX24	13.307	0.726	0.869	+12.4 ± 1.0	31.2	-0.1	-3.35	
RX29a	12.677	0.631	0.750	+13.7 ± 0.7	27.2	-1.0	-3.63	
RX30a	12.317	0.577	0.692	+15.4 ± 3.3	86.0	-1.3	-3.43	
RX34	12.658	0.745	0.850	+12.1 ± 0.6	6.1	-0.9	-4.45	1
RX35	13.278	0.801	0.937	+21 ± 10	>160	-1.6	-3.60	3
RX42	12.522	0.599	0.761	+14.2 ± 0.9	57.3	-0.9	-3.52	
RX49	13.335	0.803	1.022	+13.0 ± 1.0	<6	-0.4	-3.40	
RX52	12.528	0.577	0.709	+12.8 ± 0.6	28.4	-1.2	-4.01	
RX53	13.574	0.812	0.930	+13.6 ± 1.1	11.8	-0.4	-3.50	
RX55 ¹	12.486	0.697	0.834	+47.9 ± 1.0	<6	-1.1	-4.38	1,4
RX55 ²				-17.6 ± 1.1	<6			
RX58	13.873	0.880	1.011	+13.3 ± 1.1	12.0	-0.3	-3.81	
RX64	12.618	0.604	0.720	+13.9 ± 0.7	23.8	-1.2	-4.28	
RX66	13.350	0.946	1.161	+19.2 ± 1.1	6.0	+0.1	-3.30	1
RX69	13.169	0.722	0.826	+12.1 ± 1.1	12.8	-0.6	-3.78	
RX72a	12.623	0.617	0.763	+11.2 ± 1.1	14.5	-0.9	-3.76	
RX79	12.352	0.567	0.699	+11.8 ± 1.2	38.5	-1.0	-3.97	
RX87	13.728	0.992	1.132	+9.3 ± 1.0	14.7	+0.1	-3.39	1
RX94	13.089	0.695	0.813	+11.6 ± 1.1	29.3	-0.2	-3.31	
RX99	13.047	0.687	0.798	+11.5 ± 1.1	10.2	-0.8	-3.89	
RX101	13.143	0.706	0.883	+11.3 ± 1.1	56.5	-0.2	-3.42	

1 Possible photometric binary system.

2 Spectra were taken on both 1999 January 6 and 7 for RX12a.

3 RV and $v_e \sin i$ values taken from the H α line.

4 SB2 system. H α is not quite resolved, so only one value is given for the system.

star sequence in the V, B - V and V, V - I_c colour-magnitude diagrams (CMDs) shown in Fig. 2, possibly due to binarity. Where a target is 0.4 mag or more brighter in V than suggested by its intrinsic B - V and V - I_c, we have identified it as a *possible* binary that is unresolved by the CCD photometry in JT98. Note that the presence of an unresolved binary with period greater than a few days is unlikely to affect X-ray activity as measured by L_x/L_{bol} (although such sources should be easier to detect because of their higher L_x), but that shorter period binary systems may have enhanced X-ray activity over single stars of the same colour because of tidally enforced rapid rotation.

In summary, we believe that our sample is unbiased with respect to rotation for $(V - I_c)_0 > 0.8$, but may be missing some of the slowest rotators in a truly optically selected sample for stars hotter than this.

2.2 High-resolution spectroscopy

The stars circled in Fig. 1 and shown in Fig. 2 were observed on 1999 January 6 and 7 at high resolution using the UCLES coude echelle spectrograph on the 3.9-m Anglo-Australian Telescope. The data were collected using a 79 groove mm⁻¹ echelle grating and a 4096 by 2048 pixel MIT/LL CCD device. Each cross-dispersed echellogram covered a wide spectral range (but with gaps between orders) from about 5000 to 8500 Å, including the H α and OI 6300-Å lines. There were several orders with no telluric lines and many neutral metal lines that could be used to measure radial velocities and projected equatorial velocities by

cross-correlation with standard stars. The 1.2-arcsec slit projected to about 3.5 pixels on the CCD, leading to a resolving power of around 44 000 (or a resolution of 0.15 Å at H α). A dekker was used to separate the orders, but the spatial width of each order (about 14 arcsec) was sufficient to achieve background subtraction, given the typical 1.3–1.6 arcsec seeing that was encountered during most of the run.

Targets were observed for between 20 minutes and 1 hour, resulting in consistent signal-to-noise (S/N) levels of about 20–25 per CCD pixel. Along with the usual flats, bias and arc lamp exposures, we also obtained spectra of several radial velocity standards, a number of slowly rotating spectral type standards with minimal chromospheric activity, and a number of rapidly rotating B stars to facilitate telluric line correction around the H α and OI 6300-Å lines.

Heliocentric radial velocities (RVs) were determined for all our targets by cross-correlation with the spectra of RV standards – HR 4786, HD 4128 and HD 126053. Two orders with spectral ranges $\lambda\lambda 5157\text{--}5282$ Å and $\lambda\lambda 5989\text{--}6141$ Å were used independently with each standard. The average value is taken from all these cross-correlations, and the standard deviation is used as an estimate of the likely RV error. This is typically about 1 km s⁻¹, although it is higher for very fast rotators. The internal consistency of the measured standard RVs suggests our external error is of order 1 km s⁻¹. The RV results are presented in Table 1.

Projected equatorial velocities ($v_e \sin i$) were estimated by cross-correlation with slowly rotating stars of similar colour to the targets. The stars used were HD 102870 (F9V), HD 126053 (G1V) HD 115617 (G5V), HD 10700 (G8V), HD 4628 (K2V) and HD

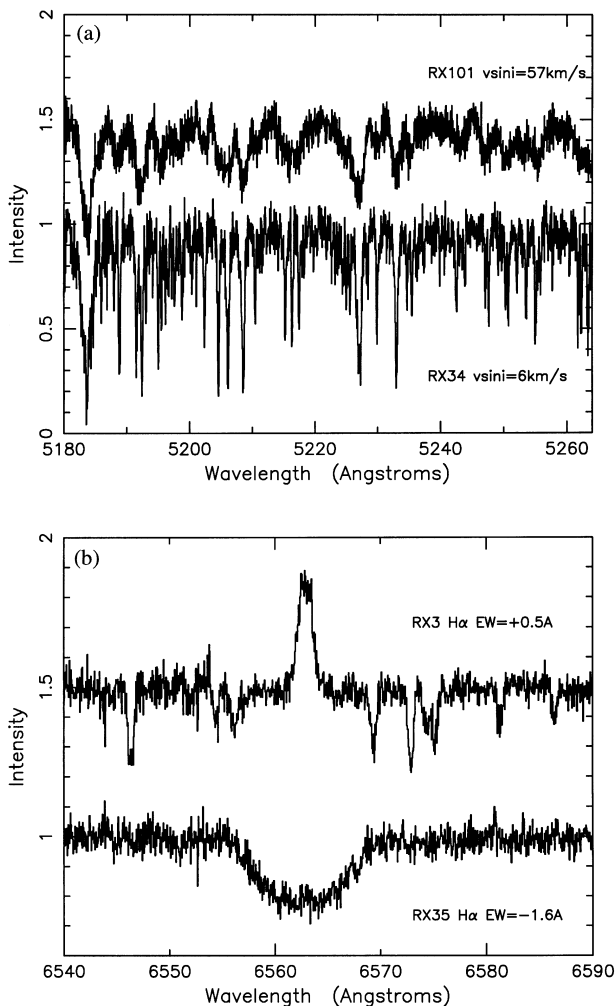


Figure 3. Examples of our high-resolution spectra. (a) One of the orders used for radial velocity and $v_e \sin i$ measurements. (b) Spectra around $H\alpha$ for two of our targets, including the ultrafast rotator RX35.

16160 (K3V). The FWHM of the cross-correlation function yields $v_e \sin i$ when calibrated by broadening the slowly rotating standards with limb-darkened rotational profiles of increasing $v_e \sin i$. At the S/N levels of our target spectra, we find that $v_e \sin i$ becomes unresolved below 6 km s^{-1} , and has a $\sim 1 \text{ km s}^{-1}$ error up to 10 km s^{-1} , and about a 10 per cent error in $v_e \sin i$ for more rapid rotators. The rotational velocities determined in this way are listed in Table 1. Fig. 3(a) shows two examples of our spectra for both rapidly and slowly rotating stars.

In all but two cases the RV cross-correlation functions were strong and single-peaked. RX55 is a probable SB2 binary system, with two clearly resolved narrow peaks in the cross-correlation functions. A $v_e \sin i$ upper limit was determined for each component. RX35 seems to be an ultrafast rotator. No clear peak could be seen in the RV cross-correlation functions, and the only notable feature in the spectrum is a very broad $H\alpha$ absorption line (see Fig. 3b). Assuming that the width of this line was due to rotational broadening, we estimate that $v_e \sin i > 160 \text{ km s}^{-1}$. The centroid of the $H\alpha$ line was used to determine the approximate RV listed in Table 1. The same technique applied to the next fastest rotator, RX30a, yields a $v_e \sin i$ of 110 km s^{-1} and an RV of $9 \pm 8 \text{ km s}^{-1}$, in reasonable agreement with the cross-correlation results.

The equivalent width (EW) of the $H\alpha$ line was measured by integration under a continuum modelled with a third-order polynomial. Telluric features were divided out approximately by reference to a rapidly rotating B-star spectrum. The EWs are listed in Table 1. For relatively slow rotators ($v_e \sin i < 30 \text{ km s}^{-1}$), the width of the $H\alpha$ feature is roughly constant, and the EWs are accurate to about 0.05 \AA . For the broader rapid rotators, the errors are more like 0.1 – 0.2 \AA and 0.3 \AA for RX35. Fig. 3(b) shows two examples of our $H\alpha$ spectra.

2.3 Cluster membership

Based on the size of the X-ray error circles and spatial density of possible optical counterparts, JT98 estimated that there would only be 0.8 spurious correlations with X-ray sources for $V < 15$ along the NGC 2547 CMD sequence. As X-ray-emitting field stars at this level of L_x/L_{bol} should be relatively rare, all but perhaps one of our targets should be NGC 2547 members. The RV measurements offer us an opportunity to check membership credentials. In a cluster, one expects the single stars to have a single RV value (for clusters with small angular extent) with a dispersion of no more than 1 km s^{-1} or so. Binary stars will introduce some scatter. Wide binaries will have RVs close to the mean single star value, close binary members could have RVs radically different from the cluster mean, and SB2 systems should have two measured RVs, either side of the cluster mean.

Consulting Table 1, we can see that 20/24 stars have RVs within 2.5σ of a weighted mean value of $+12.8 \text{ km s}^{-1}$, with a standard deviation of 0.9 km s^{-1} . The error in this mean cluster RV is dominated by the $\sim 1 \text{ km s}^{-1}$ external error in the RV values. Of the other four stars, we classify RX12a as a non-member, because we have two consistent radial velocity measurements on two different nights that are very different from the cluster mean. The only way we could be mistaken is if RX12a were a cluster SB1 with an orbital period close to the 1-day separation of the observations. However, we also note that RX12a actually lies slightly *below* the single-star sequence in Fig. 2, casting further doubt on a cluster SB1 interpretation. Because RX12a has a $v_e \sin i$ of 35 km s^{-1} though, it must be the counterpart to the X-ray source. Both RX66 and RX87 are likely to be SB1 cluster members in moderately wide binary systems, because both lie significantly above the trend of single stars in Fig. 2, and both have RVs which are only 3 – 6 km s^{-1} from the cluster mean. They are also both chromospherically active in the $H\alpha$ line (see Section 3 and Table 1), and therefore almost certainly the counterparts to the X-ray sources. Of course, we cannot rule out the possibility that they are in fact short-period systems with large velocity amplitudes, or indeed interloping field stars with very high X-ray emission – these possibilities are simply less likely. RX55 is obviously an SB2, with roughly equal-mass components judging by the nearly equal power in each of the cross-correlation peaks, and by the fact it lies about 0.7 mag above the cluster sequence in Fig. 2. The mean RV of the components is $+15.1 \pm 1.5$, very close to the cluster mean. We conclude that this is a nearly equal-mass SB2 member of the cluster. If the velocity amplitude is at least 32 km s^{-1} and the components are $1 M_\odot$, then the period is less than $74 \sin^3 i$ days, where i is the (unknown) orbital inclination. Without further information we cannot say whether the period of RX55 is short enough to tidally enforce rotation at the orbital period. The $v_e \sin i$ upper limits for the two components could be perfectly consistent with rotation periods synchronized to orbital

periods of a few days if the system has a low orbital and rotational inclination. Finally, we note that RX34 is also a possible binary system based on its position in Fig. 2, but if so, it is probably a moderately wide binary system because its RV agrees with the cluster mean.

In summary, we have strong evidence that 20 of the 24 stars we have observed are single cluster members, two are possible SB1 members, one is almost certainly an SB2 member, and one is probably a very active field star behind the cluster.

3 RESULTS

The best way to present our results is by comparison with the IC 2391 and IC 2602 clusters. These have been studied at X-ray wavelengths by Randich et al. (1995), Patten & Simon (1996) and Simon & Patten (1998), and have been the subject of an extensive optical spectroscopy campaign to establish membership and measure rotational broadening and chromospheric activity by S97. Rotation periods (as opposed to $v_e \sin i$) have also been measured in samples of cool stars in IC 2391 and IC 2602 by Patten & Simon (1996) and Barnes et al. (1999) respectively.

Our first exhibit is Fig. 1 which, as we have said previously, shows that the X-ray activity in all the clusters rises rapidly between $(V - I)_0 \approx 0.5-0.7$, but that the coronal activity peaks in IC 2391 and IC 2602 at $L_x/L_{\text{bol}} \approx 10^{-3}$, about a factor of 2 higher than in NGC 2547. The extra information we now have is that all but one of the circled NGC 2547 stars are probable cluster members, so any reduced X-ray activity levels cannot be blamed on field star interlopers. Exactly the same picture is seen in a comparison with the cool stars of the older Alpha Per cluster (this is fig. 13 in JT98 – which we do not reproduce here), but this and Fig. 1 also clearly show that at late spectral types [$(V - I_c)_0 > 1.5$, $(B - V)_0 > 1.3$] the peak level of X-ray emission in NGC 2547 returns to a level that is indistinguishable from that in the IC 2391/2602, Alpha Per or Pleiades (see Stauffer et al. 1994) late K and M stars.

Fig. 4 plots projected equatorial velocities in the clusters as a function of intrinsic colour. We are more comfortable comparing $v_e \sin i$ than attempting a comparison with the measured rotation periods in IC 2391/2602 (Patten & Simon 1996; Barnes et al. 1999), because (a) we do not have rotation periods for NGC 2547, and (b) rotation period data can be subject to additional selection biases beyond those we discuss immediately below, because of the need for substantial magnetic spot activity on the stellar surface and possible sampling biases.

Recall that we believe the NGC 2547 sample is unbiased with respect to rotation for $(V - I_c)_0 > 0.8$, but may lack some of the slowest rotators among the hotter stars. Note that in Fig. 4 and subsequent figures, we have not included the non-member RX12a, and display the SB2 system, RX55, as a single point. S97 have used similar arguments to those that we used in Section 2.1 to show that their X-ray-selected sample of G stars in IC 2391/2602 should be unbiased with respect to rotation, but that hotter and cooler stars may preferentially be the more rapidly rotating cluster members. Fig. 4 suggests that the rotation rate distributions are extremely similar, although perhaps there are one or two more slow rotators in NGC 2547 than in IC 2391/2602 where all the solar-type stars have resolved $v_e \sin i \geq 8 \text{ km s}^{-1}$. However, given the uncertainties in inclination angles and sample completeness at low rotation rates, we do not think that there is strong evidence for differences in the slowest rotation rates in NGC 2547 and

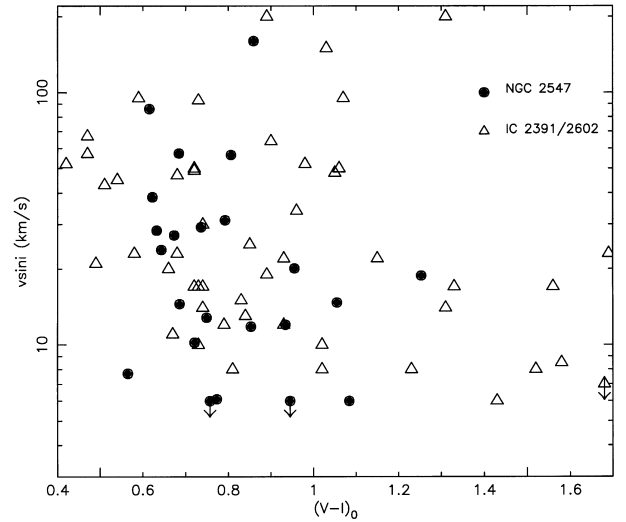


Figure 4. Projected equatorial velocities ($v_e \sin i$) as a function of intrinsic colour for NGC 2547 (dots) and IC 2391/2602 (triangles).

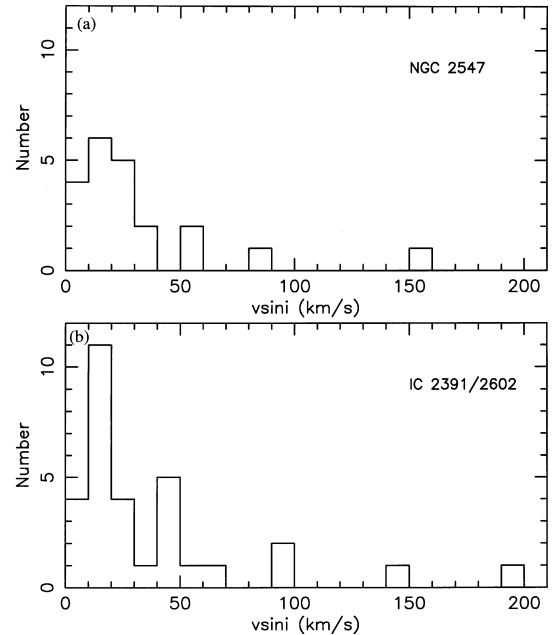


Figure 5. Histograms of $v_e \sin i$ for solar-type stars in NGC 2547 (top) and IC 2391/2602 (bottom) in the colour range $0.6 < (V - I_c)_0 < 1.1$.

IC2391/2602. Fig. 5 shows the $v_e \sin i$ histograms in NGC 2547 and IC 2391/2602 for an intrinsic colour range $0.6 < (V - I_c)_0 < 1.1$ that encompasses the bulk of the NGC 2547 sample. As the reader can see, the distributions are very similar. We have performed a formal Kolmogorov–Smirnov double-sided test between the cumulative $v_e \sin i$ distributions, which yields a probability of only 28 per cent that the NGC 2547 and IC 2391/2602 distributions are drawn from differing parent samples.

What is very clear from Figs 4 and 5 is that NGC 2547 does not appear to contain an anomalously slowly rotating population of solar-type stars. There are several late-F and G stars with $v_e \sin i \geq 20 \text{ km s}^{-1}$, the threshold for X-ray saturation in these stars defined by Stauffer et al. (1994), and four ultrafast rotators with $v_e \sin i > 50 \text{ km s}^{-1}$.

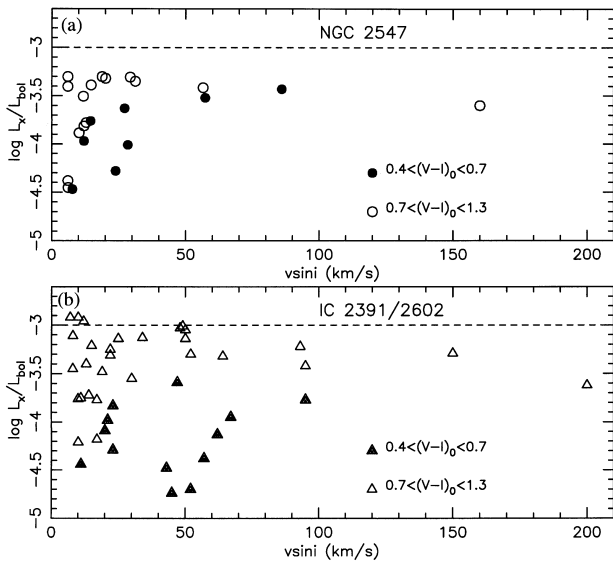


Figure 6. The X-ray activity-rotation correlations for NGC 2547 (top) and IC 2391/2602 (bottom). The samples have been split into two intrinsic colour bins: Solid symbols are for $0.4 < (V - I)_0 < 0.7$, and open symbols for $0.7 < (V - I)_0 < 1.3$.

Fig. 6 combines the rotation and X-ray data for NGC 2547 to show the rotation–activity correlation compared with that in IC 2391 and IC 2602. We have split the samples according to their colour. There is a weak correlation present for stars with $(V - I)_0 < 0.7$ in NGC 2547 and very little sign of a correlation in IC 2391 and IC 2602. We think this is because in F stars, the depth of the convection zone, rather than rotation rate, is the dominant influence on dynamo activity. If there were enough stars in these clusters, and the photometry was accurate enough, we believe that choosing a very narrow colour range *would* yield a rotation–activity correlation. This is made clearer by Fig. 1, where the X-ray activity is seen to rise steeply in the range $0.5 < (V - I)_0 < 0.7$. Small differences in colour and the randomizing effect of unknown rotation axis inclination angles can effectively destroy the correlation with rotation in this colour interval.

For cooler stars [$0.7 < (V - I)_0 < 1.3$] it does appear that X-ray activity rises with rotation rate and saturates above a $v_e \sin i$ of about $15\text{--}20\text{ km s}^{-1}$. The correlation is not perfect, probably because of random inclination angles. Stars with low $v_e \sin i$ could have high activity levels, but be fast rotators viewed close to pole-on. This may well be the case for RX49 and RX66. The key point is that NGC 2547 apparently saturates at a lower coronal activity level than IC 2391 and IC 2602, but within the limitations of the few data points we have, the saturation seems to occur at a similar rotation rate. There is also weak evidence, based only on RX35, that, as in the IC2391/2602 and Alpha Per clusters, there may be a decrease in the saturated level of X-ray emission at very fast rotation rates.

Figs 7 and 8 show the behaviour of $H\alpha$ as a function of colour in the three clusters, represented by the equivalent width (EW) of the $H\alpha$ feature. In magnetically inactive stars, $H\alpha$ is always seen in absorption, but is chromospherically filled in and then goes into weak emission ($\text{EW} \approx 1\text{--}5 \text{ \AA}$) for cooler stars in young open clusters. Fig. 7 makes the comparison between the $H\alpha$ EWs in NGC 2547 and the inactive standard stars we used for the $v_e \sin i$ comparisons. The $H\alpha$ absorption line is clearly filled or even in emission for NGC 2547 when compared with inactive stars of the same colour.

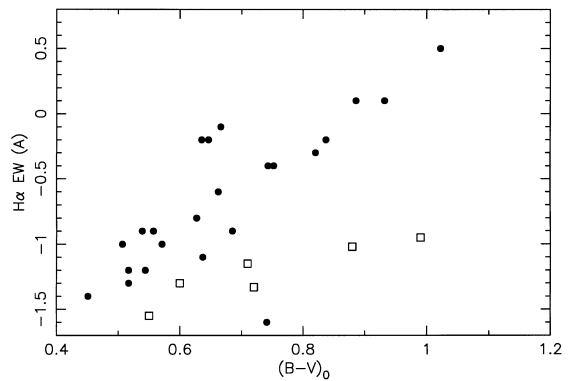


Figure 7. $H\alpha$ equivalent width versus intrinsic $B - V$ for NGC 2547 (dots) and a set of slowly rotating, low-activity stars that we used for $v_e \sin i$ cross-correlation templates (squares).

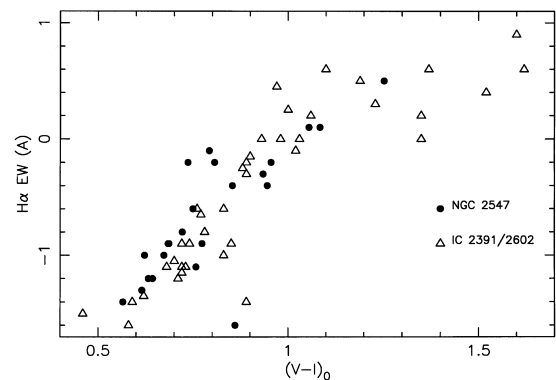


Figure 8. $H\alpha$ equivalent width versus intrinsic $V - I_c$ for NGC 2547 (dots) and IC 2391/2602 (triangles). The levels of chromospheric activity appear very similar in the three clusters.

The three NGC 2547 stars that lie above the trend for the other cluster members in Fig. 7 are RX24, RX94 and RX101. These objects do indeed have the largest $v_e \sin i$ values in this colour range. However, the correlation with rotation is certainly not perfect. RX42, with a $v_e \sin i$ of 57 km s^{-1} and a colour only slightly bluer than these three objects, lies in the sequence defined by the majority of stars. Another peculiarity is that the ultrafast rotator RX35 appears to have anomalously deep $H\alpha$ absorption for its colour, deeper even than inactive, slowly rotating stars of the same colour. We have no convincing explanation for this strange result at present. We can speculate, though, that perhaps RX35 is seen almost equator-on and is surrounded by the cool ‘slingshot prominences’ that have been seen around some ultrafast rotating field stars and G stars in the Alpha Per cluster (Collier-Cameron & Robinson 1989; Collier-Cameron & Woods 1992; Jeffries 1993). These prominences appear to be corotating clouds, confined by the stellar magnetic field, which scatter chromospheric $H\alpha$ photons out of the line of sight – causing absorption features which move from blue to red across the stellar $H\alpha$ profile. Our single 30-min observation (see Fig. 3b) may have been too long to resolve individual cloud features, or there may be many clouds around the star, because the $H\alpha$ profile appears reasonably smooth. If this explanation were true, then a highly variable $H\alpha$ profile might be expected, and our $v_e \sin i$ determination based on the width of the $H\alpha$ absorption may underestimate the true $v_e \sin i$.

Fig. 8 compares NGC 2547 with IC 2391/2602. S97 and others

have suggested that the colour at which chromospheric H α emission rises above the continuum may be an excellent indicator of rotation rates and, by implication, age, because it occurs at cooler colours in the older Pleiades and Hyades clusters. Stars with active accretion discs (the CTTS), however, show H α emission far above that seen in even the most chromospherically active stars, with emission EWs $> 10 \text{ \AA}$. This diagnostic of accretion correlates excellently with others such as near-infrared excess emission over that expected from a photosphere alone, veiling of the optical spectrum by continuum emission from accretion hotspots or emission from forbidden metallic lines such as O I at 6300 \AA (Hartigan et al. 1990; Hartigan, Edwards & Ghandour 1995). Fig. 8 demonstrates that NGC 2547 behaves very similarly to IC 2391 and IC 2602. H α emission first appears at $(V - I)_0 \approx 1.0$, which is more or less as expected for a very young cluster containing magnetically active stars. None of the stars shows any sign of excess H α that come even close to the levels expected from CTT accretion phenomena.

We have also checked our optical spectra for veiling or the presence of an O I emission line at 6300 \AA . Edwards et al. (1993) show that infrared excesses are present in stars with O I 6300 \AA EWs of between 0.1 and 10 \AA , and that such stars also show an excess optical continuum ranging from 10 per cent to >90 per cent of the observed flux. In our slowly rotating stars, we can place firm upper limits of $<0.05 \text{ \AA}$ on the EW of any O I emission, and by comparison with the low activity standard stars we find no evidence for any veiling continuum above a level of about 10–20 per cent of the observed flux. We do not detect emission lines or veiling in the fast rotators ($>20 \text{ km s}^{-1}$) either, but here the limits are relaxed to $<0.1 \text{ \AA}$ and 30 per cent respectively. In summary, we can categorically state that none of the stars we have observed shows any evidence for active accretion discs.

4 DISCUSSION

4.1 The age of NGC 2547

How we interpret the rotation data for NGC 2547 depends a great deal on what we assume its age is. JT98 obtained $14 \pm 4 \text{ Myr}$ from low-mass isochrone fits. The same isochrones would yield ages of 25 Myr for IC2391/2602, 50 Myr for Alpha Per and 90 Myr for the Pleiades, in reasonable agreement with the traditional nuclear turn-off ages determined from high-mass stars in the Hertzsprung–Russell diagram (Mermilliod 1981). In the last couple of years these ages have been challenged by measurements of the lithium depletion boundary (LDB) in very low-mass cluster stars. The luminosity at which lithium remains unburned in a fully convective star that is contracting towards the ZAMS can be mapped on to an age with reasonable precision (see Ushomirsky et al. 1998). This method has been used to obtain ages of $53 \pm 5 \text{ Myr}$ for IC 2391 (Barrado y Navascues, Stauffer & Patten 1999), $85 \pm 10 \text{ Myr}$ for Alpha Per (Stauffer et al. 1999) and $125 \pm 8 \text{ Myr}$ for the Pleiades (Stauffer, Schultz & Kirkpatrick 1998). This older age scale implies a modest amount of convective core overshoot to bring the nuclear turn-off ages into agreement (Mazzei & Pigatto 1988).

Jeffries et al. (2000) have attempted to find the LDB in NGC 2547, but could only establish a *lower* limit to the age of about 23 Myr. If the relative positions of the low-mass stars in IC 2391 and NGC 2547 are accepted as an indication of an age difference between the two clusters and we assume that the LDB age for IC 2391 is correct, then NGC 2547 could be as old as 35–40 Myr.

This would make a substantial difference in the interpretation of the rotation data, because at 40 Myr a solar-type star would have completed the vast majority of its contraction (and consequent change in moment of inertia) towards the ZAMS. At 15 Myr the surface rotation rate could still increase by about a factor of 1.8 (neglecting angular momentum loss) due to changes in radius and moment of inertia (from the models of D’Antona & Mazzitelli 1997). Also, of course, any deductions about the lifetimes of circumstellar discs are crucially dependent upon the assumed ages of the younger clusters.

Without making a judgement on the relative merits of the isochronal and LDB ages, we will need to consider the case of both the younger and older ages scales, i.e., where the ages of NGC 2547 and IC 2391 are roughly 15 and 25 Myr, and where they are roughly 40 and 55 Myr respectively.

4.2 Rotational evolution of solar-type stars

NGC 2547 (along with the IC 2391/2602 clusters) occupies an important age position between the older, well-studied Alpha Per and Pleiades clusters and PMS stars in star-forming regions. Previous attempts to study rotation in this age range (10–40 Myr) have concentrated on dispersed populations of X-ray-selected objects in and around OB and T associations (e.g. Bouvier et al. 1997b). These studies appear to show a lack of the slow rotators that are needed to explain the older Pleiades rotation distribution where 50 per cent of solar-type stars have $v_e \sin i < 10 \text{ km s}^{-1}$ (Queloz et al. 1998). The problems with these investigations of scattered PMS populations are that the stellar ages rely on rather uncertain distances, and that X-ray selection might be quite severe, thereby biasing against the presence of slow rotators. In our NGC 2547 study and in the IC 2391/2602 study of S97, it seems likely that, for solar-type stars at least, this selection effect is absent or weak.

The rotation rates we have measured in NGC 2547 largely confirm the results found in IC 2391/2602 by S97. If the clusters had ages of 40 and 55 Myr respectively, and assuming the initial angular momentum distributions and circumstellar disc lifetimes were similar, we would expect to see little difference in their rotation rate distributions. This is because solar-type stars in both clusters would have reached the ZAMS, there would be little moment of inertia change, and angular momentum losses over the course of 15 Myr might be too small to be measured, except perhaps in the few most rapid rotators. However, if the clusters were aged 15 and 25 Myr, then assuming solid-body rotation and ignoring angular momentum losses, we might expect to see a rotational spin-up of 50 per cent between NGC 2547 and IC 2391/2602. The median $v_e \sin i$ among the solar-type stars [$0.6 < (V - I_c)_0 < 1.1$] in NGC 2547 is about 20 km s^{-1} and very similar in IC 2391/2602. These figures are based on relatively small numbers, but one could view this similarity as a (very) weak argument for the older age scale.

The upper quartile of rotation in the Pleiades solar-type stars occurs for $v_e \sin i > 15 \text{ km s}^{-1}$. In IC 2391/2602 it is 50 km s^{-1} , and about 40 km s^{-1} in NGC 2547. The numbers here really are too small to analyse any difference between NGC 2547 and IC 2391/2602. If the solar-type stars in all three clusters have completed their PMS contraction, then taken together, the results indicate that if they rotate as solid bodies, the most rapidly rotating stars must lose 60–70 per cent of their angular momentum between 40–50 Myr and $\sim 125 \text{ Myr}$. If the clusters are younger,

then the amount of angular momentum loss must be even greater (80–90 per cent) to allow for some contraction and spin-up on to the ZAMS. The similarity in $v_e \sin i$ of the rapid rotators of NGC 2547 and IC 2391/2602 argues for similar initial conditions and circumstellar disc lifetimes.

Overall, what we have measured is in very good agreement with the models put forward by Bouvier et al. (1997a). These models start with an observed rotation rate in T Tauri stars, and evolve this using wind angular momentum loss (which saturates at fast rotation rates) and early coupling to a circumstellar disc which is responsible for the predominance of slow rotators at later times. These solid-body rotation models predict maximum rotational velocities of order $150\text{--}200\text{ km s}^{-1}$ for ages 15–40 Myr and that roughly half the solar-type stars in NGC 2547 should have $v_e \sin i < 20\text{ km s}^{-1}$, which is what we have measured. This high proportion of slow rotators is achieved by assuming circumstellar disc lifetimes as old as 40 Myr in some stars and that about 15 per cent of stars (the slowly rotating ones) are locked to their discs at 15 Myr.

We have no evidence that any of the solar-type stars in NGC 2547 still have discs. This could argue that the cluster has an age of ~ 40 Myr, but other interpretations are possible. Cameron & Campbell (1993) and Armitage & Clarke (1996) show that discs with mass accretion rates of only $10^{-10} M_\odot \text{ yr}^{-1}$ can still enforce rotational equilibrium, whereas mass accretion rates at least an order of magnitude higher are needed to provoke the optical accretion signatures we have searched for in this paper. Some of our slowest rotators may still have remnant discs, and it would be worth searching for these in more detail at infrared wavelengths. Another possibility is that the radiative core and convective envelope are not perfectly coupled, and that interior differential rotation is possible. This would allow less angular momentum loss to produce slow rotators, and thus requires shorter disc lifetimes. However, the core–envelope coupling time-scale must be substantially greater than the 10 Myr proposed by Keppens et al. (1995), who found that short disc lifetimes (~ 6 Myr) could not produce enough slow rotators on the ZAMS in these circumstances. The differential rotation models put forward by Krishnamurthi et al. (1997) show that sufficient slow rotators *can* be produced with disc lifetimes of 3–10 Myr if the core–envelope coupling timescale is of order 100 Myr.

Alternatively, NGC 2547 and IC 2391/2602 may have been born with a population of slower rotators than are typically seen in even younger clusters and star-forming regions. Barnes et al. (1999) show that to explain the slow rotators in IC 2602 requires that 20–30 per cent of solar-type stars in IC 2602 needed to have initial periods as short as 16 d if disc lifetimes are to be limited to ≤ 3 Myr. However, Choi & Herbst (1996) and Kearns & Herbst (1998) find that 90 per cent of stars in the 3-Myr-old NGC 2264 cluster and the 1-Myr-old Orion nebula and Trapezium clusters have rotation periods shorter than 10 d. Thus, long disc lifetimes (> 10 Myr), or internal differential rotation with long core–envelope coupling timescales (~ 100 Myr), or anomalously small initial angular momenta are required to explain the slow rotators in NGC 2547, IC 2391 and IC 2602.

In any of these scenarios it is at least clear that the NGC 2547 (and IC 2391/2602) data have partially solved the problem of the lack of slow rotators at ages between the PMS stars in Taurus and Orion and the older Alpha Per and Pleiades clusters. The slow rotators are there; it just requires observations of optically selected samples, or at least complete X-ray-selected samples which are not biased against slow rotators, to reveal them. We can also say

that the combination of initial angular momentum distribution and disc lifetimes must be reasonably similar in NGC 2547 and IC 2391/2602 in order to produce similar $v_e \sin i$ distributions at their current ages. This is an important result because in the disc-regulated angular momentum loss model, even a small variation in disc locking timescales would produce big changes in the $v_e \sin i$ distribution as solar-type stars reached the ZAMS.

4.3 Anomalous X-ray emission in NGC 2547

Our main reason for performing high-resolution spectroscopy in NGC 2547 was to explain the anomalously low level of X-ray emission in the most active solar-type stars in the cluster. Our working hypothesis was that all of the NGC 2547 late-F and G stars were rotating slower than 20 km s^{-1} , and hence none of them showed the saturated level of X-ray emission seen in other young clusters. Our data conclusively reject this hypothesis. There are several examples of very rapid rotators in NGC 2547, and the rotation rate distribution is indistinguishable from that of the IC 2391 and IC 2602 clusters.

We had also suggested that slow rotation in NGC 2547 might be caused by long-lived circumstellar discs or an unusually small amount of initial angular momentum. Neither of these is now required, and we have evidence that none of the solar-type stars in NGC 2547 possess active accretion discs. This latter discovery in itself places an upper limit on the lifetime of such discs (that could be detected with H α , O I emission or optical veiling) of 40 Myr and possibly as low as 15 Myr, depending on what is finally concluded about the age of NGC 2547.

NGC 2547 appears to follow the ARAP discussed in the introduction up to a point. The levels of activity are appropriate for its age and measured rotation rates, except for the case of coronal activity in the fastest rotators. There, the ‘saturation level’ for X-ray emission is a factor of 2 lower than that seen in all other young clusters, but appears to occur at similar rotation rates of $15\text{--}20\text{ km s}^{-1}$.

The fact that the X-ray saturation occurs at a similar rotation rate, and that the chromospheric activity in NGC 2547 concurs with that in IC 2391 and IC 2602, leads us to suspect that perhaps the X-ray fluxes in NGC 2547 have been underestimated by a factor of 2. A further piece of evidence in support of this view is that RX12a, which is almost certainly a background field star, has $v_e \sin i = 35.5\text{ km s}^{-1}$ and $L_x/L_{\text{bol}} = 10^{-3.42}$. The spectral type of this object (determined from the cross-correlations) is about K0V, so it does not appear to suffer from much more reddening or absorption than the NGC 2547 stars. If the low X-ray saturation levels in NGC 2547 are peculiar to that cluster for some reason, then it is difficult to explain why a similar phenomenon occurs in an unconnected fast rotating field star in the same direction.

A factor of 2 underestimate of intrinsic X-ray fluxes might be possible if the interstellar absorption towards the cluster is higher than assumed by JT98, or if the assumed stellar X-ray spectrum is incorrect. Another factor to consider is that the IC 2391, IC 2602, Alpha Per and Pleiades *ROSAT* data we have discussed were obtained with the Position Sensitive Proportional Counter (PSPC), rather than with the High Resolution Imager (HRI) as in the case of NGC 2547. However, we do not believe there could be as much as a factor of 2 error produced here. The assumed interstellar column density for NGC 2547 of $3 \times 10^{20}\text{ cm}^{-2}$ was estimated from the cluster reddening (Bohlin, Savage & Drake 1978) and from Lyman α measurements of early-type stars at similar

galactic coordinates (Fruscione et al. 1994). A likely error in these estimates is 50 per cent, but the column density would have to be as high as $(2-3) \times 10^{21} \text{ cm}^{-2}$ to double the unabsorbed X-ray fluxes in NGC 2547. Such a large column density probably exceeds the column density out of the Galaxy in this direction, as deduced from 21-cm maps (Marshall & Clark 1984). JT98 also assumed a 1-keV optically thin plasma, but again the consequences of this coronal temperature being wrong by as much as 50 per cent changes X-ray fluxes by only 15 per cent (David et al. 1996). Also, we cannot appeal to a mismatch in the calibrations of the PSPC and HRI. Simon & Patten (1998) have measured X-ray fluxes for stars in IC 2391 with the HRI and compared them with fluxes measured for the same stars with the PSPC by Patten & Simon (1996). They find excellent agreement, with essentially no systematic difference and little variability in the X-ray fluxes. The HRI count rate to flux conversion factor used by Simon & Patten is 10 per cent smaller than that used for NGC 2547 by JT98, but this is consistent with the smaller assumed value of interstellar absorption for IC 2391. Lastly, we can also say that the bolometric corrections used by various authors to calculate L_x/L_{bol} are the same to within a few hundredths of a magnitude at all colours, so that none of the discrepancy can be attributed to differences in these corrections.

Our other line of argument for claiming that JT98 calculated the fluxes correctly is more indirect. It seems that the peak levels of X-ray activity in the M stars of NGC 2547 are very similar to those in IC 2391/2602 and other clusters. Fig. 1 shows that this is the case. Note that we have not tried to compare mean X-ray emission in these cool stars, because the samples are incomplete and heavily biased towards the most active stars. A global factor of 2 increase in all the X-ray fluxes in NGC 2547 would shift its M dwarfs to activity levels higher than those seen in other clusters. The only way of escaping this problem would be if the solar-type stars were more absorbed or had radically different coronal spectra to the M dwarfs. Neither of these possibilities seems likely, but we will be able to rule them out when we have X-ray spectra from the *Chandra* or *XMM* satellites.

We have also considered compositional differences between the clusters as a possible solution. Different metallicities could affect convection zone depths and dynamo activity, or may simply alter the coronal abundances and emission measure distributions. The metallicities of these three young open clusters are not expected to depart strongly from solar values, but they remain undetermined at the present time. However, we have interpreted the strong turn-on of X-ray activity at $0.5 < (V - I)_0 < 0.7$ as due to the onset and deepening of convection zones in F stars. The fact that this occurs at very similar intrinsic colours in NGC 2547, IC 2391 and IC 2602 argues that any compositional differences between the clusters are small and do not greatly influence the magnetic dynamo efficiency.

We are left with a puzzle, perhaps akin to the very different X-ray luminosity functions in the older (600 Myr) Hyades and Praesepe clusters (Randich & Schmitt 1995; Barrado y Navascués, Stauffer & Randich 1998), which also remains unexplained and does not seem likely to result from very different rotational properties. That clusters with similar ages can have different X-ray properties means we must be careful about using X-ray data and the ARAP to draw conclusions about the age distributions of arbitrary samples of stars, whether in clusters or the field.

5 SUMMARY

We have obtained high-resolution spectroscopy for a sample of

solar-type stars in the young open cluster NGC 2547. We have determined projected equatorial velocities, searched for the presence of active accretion discs, and measured their chromospheric activity. Our main conclusions can be summarized as follows.

(1) The rotation rate distribution in NGC 2547 is indistinguishable from that in the slightly older IC 2391 and IC 2602 clusters. In the current paradigm for the rotational evolution of cool stars, this points to very similar initial conditions and circumstellar disc lifetimes in the three clusters.

(2) We find both examples of ultrafast rotating stars and of stars with $v_e \sin i < 10 \text{ km s}^{-1}$. If the slowly rotating stars evolve from populations with the rotation rate distributions seen in very young PMS clusters, then either very long ($\sim 10-40$ Myr) disc lifetimes or internal differential rotation are required. An alternative might be that NGC 2547 (and IC 2391/2602) were born with a high proportion of anomalously slowly rotating objects.

(3) We find no evidence for active accretion discs in our sample. This sets an upper limit to the lifetime of such discs at 15–40 Myr, depending on what is assumed for the age of NGC 2547.

(4) The slowly rotating objects in NGC 2547 (and IC 2391/2602) have no counterparts in the X-ray-selected samples of 10–40 Myr PMS stars that have been studied previously. We ascribe this to biases towards fast rotators caused by strong X-ray selection. We believe that this bias is weak or absent in our sample of solar-type stars.

(5) NGC 2547 appears to follow the same rotation–activity correlation as that seen in other young clusters. X-ray activity increases up to a saturated peak for $v_e \sin i > 15-20 \text{ km s}^{-1}$. However, we are unable to explain why the X-ray activity of solar-type stars in NGC 2547 saturates at $\log(L_x/L_{\text{bol}}) = -3.3$, a factor of 2 lower than in other young clusters. We rule out slow rotation, and consider significant uncertainties in calculating the X-ray fluxes unlikely.

ACKNOWLEDGMENTS

This work was based on data collected at the Anglo-Australian Observatory, partly funded by the UK Particle Physics and Astronomy Research Council (PPARC). We thank the staff of the Anglo-Australian Observatory for assistance during the observations. Computational work was performed on the Keele and St Andrews nodes of the PPARC-funded Starlink network.

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