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# PRE–MAIN-SEQUENCE STARS IN THE YOUNG CLUSTER IC 2391

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## ABSTRACT

We have identified a small number of new, low-mass members of the young open cluster IC 2391. The faintest previously known members of the cluster have $V \simeq 11$, slightly brighter than the expected pre–main-sequence turnon for the cluster. Our members extend to $V = 14.2$, and most of the newly identified members are displaced well above the main sequence. The new members fall approximately along a $3 \times 10^7$ yr isochrone—the age estimated for the cluster on the basis of its upper main-sequence turnoff. The dispersion about the isochrone is small, indicating that our sample of stars has an age spread of at most $2 \times 10^7$ yr.

We have also obtained echelle spectra for the probable cluster members. Most show Hα in emission, a strong lithium 6707 Å absorption line, and a few are rapid rotators ($v \sin i \simeq 100$ km s$^{-1}$). The lithium abundances for stars cooler than the Sun in IC 2391 are considerably less than the primordial lithium abundance, providing the first direct evidence for substantial pre–main-sequence lithium burning. The rotational velocities show a range from $\sim 15$ to 150 km s$^{-1}$, with a distribution of rotational velocities not significantly different from that observed for low-mass stars in the Pleiades. We had previously argued that the rotational velocity distribution for the low-mass stars in the Pleiades could be taken as evidence for a large (several $\times 10^7$ yr) age spread among those stars. Because the low-mass stars in IC 2391 obtain a similar rotational velocity distribution without a significant age spread, the simple interpretation of the Pleiades rotational velocity data is no longer valid, and any evidence for an age spread among the low-mass stars in that cluster must arise elsewhere.

*Subject headings:* clusters: open — stars: emission-line — stars: evolution — stars: pre–main-sequence

## I. INTRODUCTION

Low-mass T Tauri stars still in the fully convective phase of their pre–main sequence (hereafter PMS) evolution generally have quite small rotational velocities (Hartmann *et al.* 1986; Bouvier, Bertout, and Mayor 1986). In contrast to the T Tauri stars, a large fraction of the stars in the mass range 0.5–1.0 $M_\odot$ are observed to have quite large rotational velocities shortly after their arrival on the main sequence (Stauffer *et al.* 1984, 1985; Stauffer and Hartmann 1987). The latter result is not contradictory to the T Tauri observations because contraction during the PMS phase predicts increases in surface rotational velocities of the order observed if angular momentum loss between the T Tauri and main-sequence phases is small. One fact of the observations is difficult to understand, however. The rotational velocities for the T Tauri stars (Bouvier, Bertout, and Mayor 1986) show a relatively small dispersion with very few stars having either less than half or more than twice the mean rotational velocity. The low-mass stars in the Pleiades (Stauffer and Hartmann 1987, hereafter SH87) and Alpha Persei clusters (Stauffer *et al.* 1985) instead show a large number of slowly rotating stars ($v \sin i < 15$ km s$^{-1}$) and a long tail to high rotational velocities (up to 200 km s$^{-1}$). Assuming the essential difference between the T Tauris and the cluster stars is evolutionary, this comparison may indicate either a significant spread in ages for the cluster stars or an angular momentum loss rate during the PMS stage that is essentially independent of rotation rate (SH87). A test of these two mechanisms can be made via observation of a moderately rich open cluster with an age intermediate between the T Tauri stars and Alpha Persei (age $\simeq 5 \times 10^7$ yr).

Two nearby, southern open clusters, IC 2391 and IC 2602, have ages appropriate for the rotational velocity evolution test. Both clusters have distances of order 150 pc and ages of order $3 \times 10^7$ yr (Mermilliod 1981). Unfortunately, no faint membership studies have been published for either cluster, and finding low-mass members has proved a difficult task. We report here our attempts to locate low-mass members of IC 2391, and the initial results of a spectroscopic survey of these stars.

Photometry and proper motions have been obtained for the brighter members of IC 2391 by Hogg (1960) and Lynga (1959, 1961). Spectroscopy of the brighter stars has been reported by Feinstein (1961), Buscombe (1965), Perry and Bond (1969), and Levato and Malaroda (1984). These authors have shown that the upper main sequence of the cluster contains of order 20 members brighter than $M_V = 4$. Hogg (1960) suggested that a

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few members fainter than that limit appear to be PMS stars. Distance moduli for the cluster derived from photometric and spectroscopic techniques indicate $(m - M) = 6.05 \pm 0.2$, and a quite small reddening [$E(B-V) \simeq 0.04$; Becker and Fenkart 1974].

## II. OBSERVATIONS

### *a) Sample Selection*

The faintest published membership list for IC 2391 extends to only $V \approx 11$ ($M_V \simeq 5$). Because we are primarily interested in G and K dwarf members of the cluster, it was necessary for us to attempt to identify fainter candidate cluster members. The primary method employed was a proper motion survey, the details of which will be discussed more fully in a separate paper (McNamara 1987). Briefly, first epoch plates from the Mount Stromlo 74" reflector from 1958 were combined with second epoch plates from the Yale-Columbia 26" refractor for the survey. The plates were measured with the Automatic Measuring Engine (AME) of Lick Observatory. The region surveyed was $\sim 48' \times 41'$ in area, approximately centered on the cluster center. Proper motions for 883 stars in the magnitude range $12 < V < 16$ were derived. An attempt was made to fit the vector point diagram for these proper motions with two elliptical Gaussian distributions representing the field and cluster populations (Vasilevskis *et al.* 1958). However, so few cluster stars appear in the diagram that it was not possible to determine the parameters for the cluster distribution or to estimate probabilities of membership in the cluster. Instead, we simply identified stars with proper motions near that observed for the high-masss stars in the cluster as candidate cluster members.

The proper motion survey did not cover the entire region of the cluster because the image quality at the edge of the reflector plates was poor. In order to extend our search for cluster members to a wider region, we selected 70 stars in approximately the same magnitude range as the proper motion survey but outside the area of the sky covered by the proper motion survey. Finally, we also added a number of the stars identified by Hogg (1960) as possible faint cluster members to our observing list.

### *b) Photometry*

BVRI observations for the candidate IC 2391 members were obtained at CTIO during 1985 February using the 1.5 m telescope and the "Patch" photometer with a GaAs phototube. The photometry was reduced to standard photometric systems (Johnson *B*, *V*; Kron *R*, *I*) using calibration stars from Landolt (1983), Kron, Gascoigne, and White (1957), and Moffett and Barnes (1979). For most of the stars observed, the photometry should have 1 $\sigma$ accuracies of order 0.015 mag, based on the dispersion of the standard stars about their nominal values.

Photometry was obtained for $\sim 150$ stars in the neighborhood of IC 2391. Very few of those stars are members, however, as can be deduced from inspection of a color-magnitude diagram for the sample (Fig. 1). The curve in Figure 1 is a $3 \times 10^7$ yr isochrone from the PMS evolutionary calculations of Vandenberg (1987). There is no obvious concentration of points near the isochrone.

A somewhat more productive means of identifying possible cluster members is obtained by examining a $B-V$, $R-I$ plot of the stars observed (Fig. 2). The curve in this figure is a fit to the photometry for Pleiades members (Stauffer 1982, 1984). Because the Pleiades has approximately the same reddening and age as IC 2391, members of the cluster should fall along this line. The large number of stars with $B-V > 1.4$ and with $R-I > 0.6$ are presumably reddened background stars and can be excluded from further consideration. Bluer than $B-V = 1.2$ most stars fall near the Pleiades locus, and the two-color diagram does not serve as a strong membership criterion.

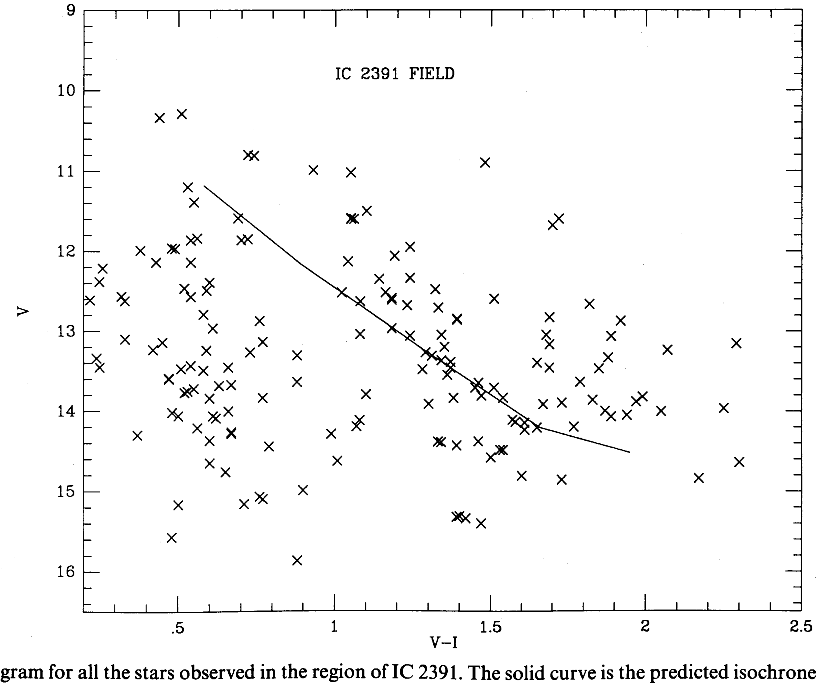

FIG. 1.—Color-magnitude diagram for all the stars observed in the region of IC 2391. The solid curve is the predicted isochrone for stars with age = $3 \times 10^7$ yr.

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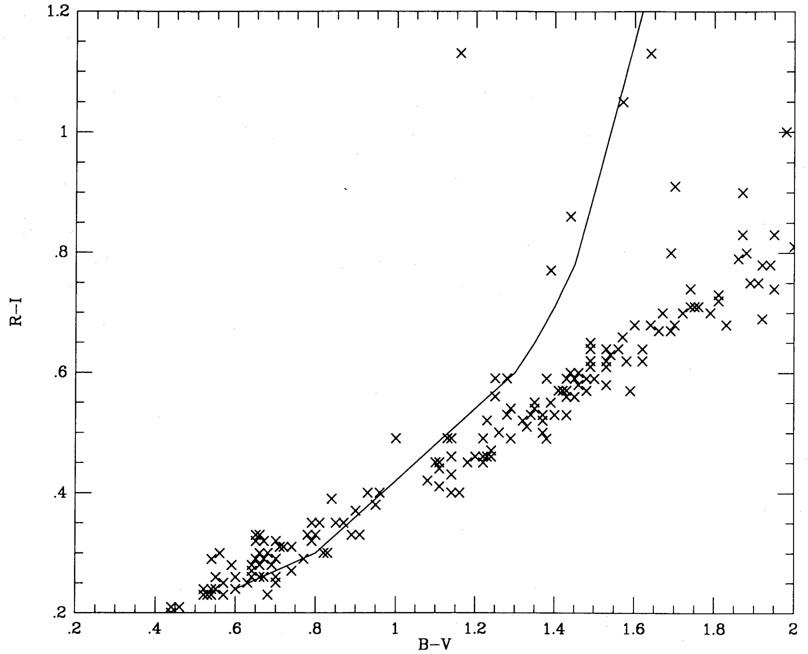

FIG. 2.—$B-V$ vs. $R-I$ colors for the stars observed towards IC 2391. The curve is a fit to photometry of members of the Pleiades cluster.

### c) *Echelle Spectroscopy*

High-resolution spectra for a small sample of the IC 2391 candidate members were obtained following the photometry run at the CTIO 4 m telescope. The Air Schmidt camera, a 31.6 l/mm echelle grating, and the 226 l/mm cross grating were used. The detector was a GEC CCD (425 × 576 pixels). A 300 $\mu$m (2″ on the sky) slit was employed. Full wavelength coverage was obtained from ∼5700–6900 Å, with a dispersion of ∼0.2 Å pixel$^{-1}$. Bias subtraction, flat-fielding, and bad-pixel removal routines were applied to each frame using standard techniques. The separate echelle orders were extracted using the Lick Observatory VISTA reduction package. Thorium-argon spectra obtained periodically during each night were used to derive wavelength calibrations for each order (third-order fits, generally). The individual order spectra were then rebinned to a constant dispersion, the echelle blaze removed via division by a continuum source, and all the orders combined to yield a single high resolution spectrum. The final spectra were analyzed for radial and rotational velocities using a cross-correlation package that we have described elsewhere (Hartmann *et al.* 1987).

In all, 40 candidate IC 2391 stars were observed spectroscopically. The stars selected were preferentially those with proper motions or colors suggestive of membership. Of the stars observed, 9 or 10 appear to be cluster members, based on the presence of moderately strong lithium 6707 Å, H$\alpha$ emission, and radial velocities consistent with that expected. The radial velocities of the proposed members range from 16 to 22 km s$^{-1}$. Because the internal velocity dispersion of the cluster should be less than 1 km s$^{-1}$, this indicates that our velocity accuracy is only of order 3–4 km s$^{-1}$. This is much worse than velocities we have obtained for other clusters (Stauffer *et al.* 1985; SH87), presumably due to the considerably lower dispersion (0.2 Å pixel$^{-1}$ vs. 0.04 Å pixel$^{-1}$ at the MMT) of the CTIO echelle and our inexperience with using this instrument for radial velocity work.

We examined all the spectra for H$\alpha$ emission and lithium absorption, since both features are generally indicative of youth. Tables 1 and 2 provide the positions, photometry, radial and rotational velocities, lithium equivalent widths (in Ångstroms) and an indication of whether H$\alpha$ is in emission or absorption for all of the stars believed to be probable cluster members. Stars 1–2 and 6–10 have proper motions suggestive of cluster membership; stars 3–5 do not have measured proper motions and were selected for spectroscopic observation because our photometric survey showed that they have colors compatible with cluster membership. Six of the proposed members show strong lithium, and five show H$\alpha$ in emission. All of the stars with the spectroscopic indicators of youth have radial velocities consistent with cluster membership. The proposed cluster members without H$\alpha$ in emission are generally bluer than $B-V \simeq 1.0$, and generally have strong lithium absorption lines. The later type stars generally have H$\alpha$ emission but no detectable lithium. Two of the late-type stars without obvious lithium have $v \sin i > 90$ km s$^{-1}$, so the lack of detectable lithium absorption in part reflects the difficulty of measuring weak, broad lines. Because only very young K

TABLE 1

POSITION FOR IC 2391 MEMBERS

| SHJM | Star[a] | R.A.(1950) | Decl.(1950) |
|---|---|---|---|
| 1……… | H28 | $8^{h}37^{m}29^{s}.3$ | – 52°47′16″ |
| 2……… | H35 | 8 41 20.0 | – 52 50 20 |
| 3……… |  | 8 40 00.5 | – 53 11 58 |
| 4……… |  | 8 42 00.9 | – 52 46 51 |
| 5……… |  | 8 42 00.9 | – 52 46 48 |
| 6……… |  | 8 38 27.2 | – 52 47 17 |
| 7……… |  | 8 40 26.0 | – 52 55 59 |
| 8……… |  | 8 40 13.5 | – 52 48 49 |
| 9……… |  | 8 40 31.3 | – 52 41 28 |
| 10……… |  | 8 40 52.1 | – 52 51 08 |

[a] H28 and H35 are from Hogg 1960.

TABLE 2

Observational Data for IC 2391 Members

| Star | $V$ | $B-V$ | $V-R$ | $R-I$ | $cz$ | $v \sin i$ | Lithium Equivalent Width | Hα Emission? |
|---|---|---|---|---|---|---|---|---|
| 1...... | 10.29 | 0.68 | 0.28 | 0.23 | 21 | 34 | $0.16 \pm 0.01$ | No |
| 2...... | 10.34 | 0.57 | 0.21 | 0.23 | 22 | <15 | $0.14 \pm 0.01$ | No |
| 3...... | 12.63 | 1.00 | 0.59 | 0.49 | 19.5 | 90 | $0.13 \pm 0.07$ | Yes |
| 4...... | 14.21 | 1.39 | 0.92 | 0.77 | 22.5 | <15 | <0.05 | Yes |
| 5...... | 14.21 | 1.39 | 0.92 | 0.77 | ... | 150 | <0.2 | Yes |
| 6...... | 11.86 | 0.84 | 0.40 | 0.31 | 19.5 | 16 | $0.19 \pm 0.01$ | No |
| 7...... | 12.52 | 1.10 | 0.57 | 0.45 | 16.5 | <15 | <0.05 | No |
| 8...... | 13.38 | 1.25 | 0.76 | 0.60 | 16.5 | 18 | $0.09 \pm 0.03$ | Yes |
| 9...... | 13.48 | 1.25 | 0.72 | 0.56 | 19 | <15 | $0.10 \pm 0.03$ | Yes |
| 10...... | 14.00 | 1.44 | 1.01 | 0.86 | 17 | 95 | <0.1 | Yes |

Notes.—Stars 4 and 5 are separated by ~3″ and have nearly the same brightness as judged by eye. The photometry refers to the pair, except the observed $V$ magnitude ($V = 13.46$) has been divided equally between the two stars.

dwarfs have such large rotational velocities, membership in IC 2391 is assured in any event. The weakest case for cluster membership of the stars in Table 1 is star 7, a slowly rotating, early K dwarf according to our observations. The radial velocity and photometry for star 7 are consistent with cluster membership, but Hα is in absorption and there is little or no lithium feature. Hα in absorption is not necessarily contradictory to membership for stars of this color, so it is only the lack of lithium that argues critically against cluster membership. We retain the star as a possible member because of the large spread in lithium equivalent widths observed for stars of approximately the same color in the Pleiades (Duncan and Jones 1983). Finding charts for the stars proposed as cluster members are provided in Figure 3 (Plates 9–10).

A montage of spectra of the proposed cluster members, covering 6450–6750 Å is shown in Figure 4. Both rapid rotators, SHJM 10 and particularly SHJM 4, have Hα emission broader than the photospheric absorption lines. A histogram depicting the radial velocity distribution for all the stars observed is provided in Figure 5. Stars with strong lithium absorption or Hα emission are indicated in the figure in order to illustrate the good separation between cluster and field stars. An HR diagram for the probable cluster members is provided in Figure 6. The lower curve in Figure 6 is a fit to the Pleiades main sequence. The upper curve is a $3 \times 10^7$ yr isochrone adopted from VandenBerg (1987), but shifted vertically ~0.2 mag so that the theoretical main sequence approximately matches the observed one. Figure 7 shows the rotational velocity distribution for IC 2391, plotted versus the reddening corrected $V-I$ color for the star. The most interesting facet of the figure is the presence of the slowly rotating stars over the entire color range observed. These stars will be discussed in more detail in the next section.

## III. DISCUSSION

### *a) Rotational Velocity Distribution*

The late-type stars in Figure 6 all lie near the $3 \times 10^7$ yr isochrone, indicating that the stars observed all have approximately the same age. Isochrones for 25 and $45 \times 10^6$ yr comfortably enclose all of the stars observed except SHJM 10, indicating an upper limit to the age spread of $\sim 2 \times 10^7$ yr. Because other factors (duplicity, spottedness, errors in the photometry) also contribute to a spread about a single isochrone, the observations are also consistent with essentially no age spread. Selection effects may have caused us to miss either much younger or older cluster members, so we cannot exclude a larger age spread for the cluster as a whole than is apparent in Figure 6. However, for the stars observed, an age spread larger than 1–2 $\times 10^7$ yr is not likely to provide a viable explanation for variations in other features.

The rotational velocity distribution for stars later than about G0 in IC 2391 consists of a set of stars rotating at or below 20 km $s^{-1}$, and another set of very rapidly rotating stars with $v \sin i > 90$ km $s^{-1}$. This distribution is puzzling, because low-mass T Tauri stars appear to have a relatively small range in rotational velocities. If the differences between the T Tauri and IC 2391 rotational velocity distributions are assumed to be entirely evolutionary (and not due to differing initial angular momentum distributions or problems with small number statistics for IC 2391), the new observations place strong constraints on the role of angular momentum loss during PMS evolution. According to VandenBerg's evolutionary tracks, a 0.7–0.8 $M_\odot$ star should have its surface rotational velocity increase between $L_{\rm BOL} \simeq 0$ on the Hayashi track, where most T Tauri stars are observed, and the $3 \times 10^7$ yr isochrone by about a factor of 3.5 if solid body rotation is assumed and if there is no angular momentum loss. Since the most rapidly rotating low-mass T Tauri stars have $v \sin i = 30$–35 km $s^{-1}$, this leaves little room for any angular momentum loss during this time period if the IC 2391 rapid rotators are to be explained. Conversely, the slowly rotating IC 2391 members either require considerable angular momentum loss during this period, or their progenitors must be only the most slowly rotating T Tauri stars (which have $v \sin i \simeq 8$ km $s^{-1}$ according to Bouvier *et al.* 1987).

The Pleiades and Alpha Persei cluster late-type stars also show rotational velocity distributions with a large number of slow rotators and a tail of rapid rotators (SHBJ, SH87). We have previously reconciled that distribution with the T Tauri observations by postulating that either the open cluster stars have a considarable age spread (and thus the slow rotators are the older stars that have spun down) or that angular momentum loss rates are essentially independent of Ω, the angular rotation rate, above some critical rotational velocity. The former explanation is ruled out for IC 2391 because we know all the stars observed have about the same age. The latter explanation may be viable for IC 2391. Any angular momentum loss rate with feedback, that is where $dJ/dt \sim \Omega^N$ for $N > 1$ (such as the Skumanich law), narrows the range of

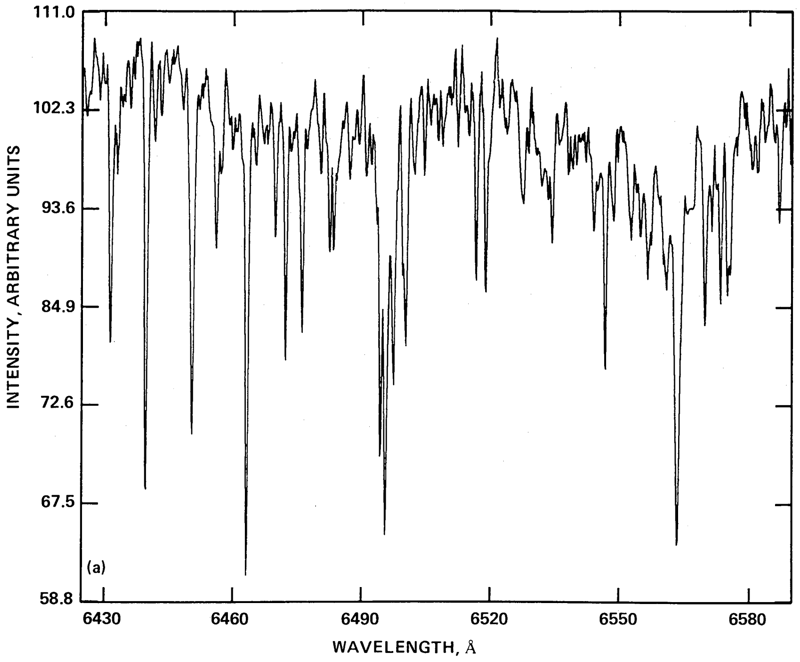

FIG. 4*a*

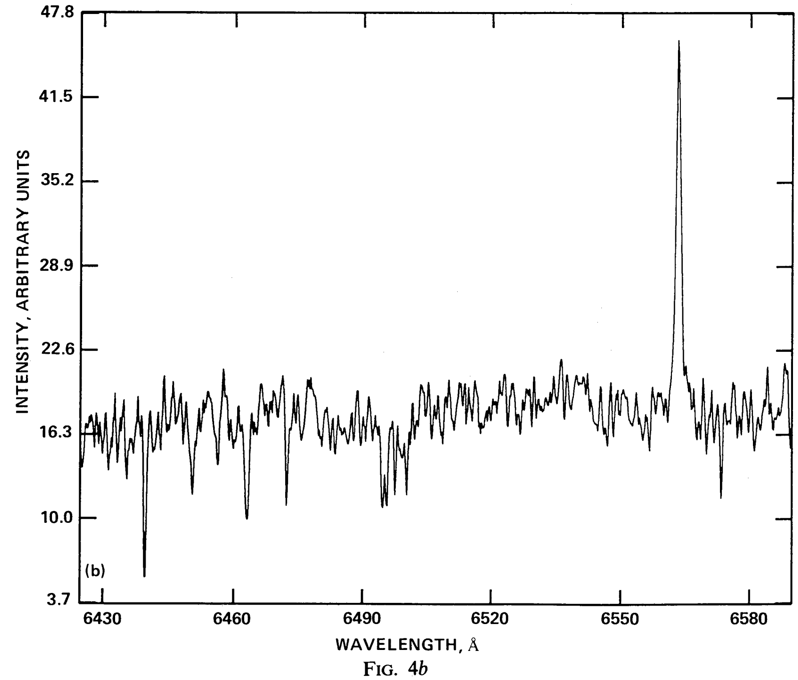

FIG. 4*b*

FIG. 4.—(*a*–*d*) Spectra of some of the proposed late-type members of IC 2391. Note the presence of Hα emission in several of the stars. The stars shown are (*a*) SHJM 6, (*b*) SHJM 5, (*c*) SHJM 10, and (*d*) SHJM 4.

stellar angular momenta with increasing age for a group of stars. That clearly is not satisfactory here. However, if $dJ/dt$ = constant for these PMS stars (assuming they are all above the critical rotation rate), the dispersion in rotational velocities could increase between the T Tauri stage and $3 \times 10^7$ yr. The bimodal velocity distribution in IC 2391 in fact suggests that an angular momentum loss rate with negative feedback ($dJ/dt \sim \Omega^{-N}$) might fit the data better. The small number of stars observed precludes any weight being attached to that suggestion.

An alternate explanation which may be simpler is that the initial distribution of angular momentum for low-mass stars in clusters is different from that for low-mass stars in associations. That is, perhaps the initial distribution of angular momentum in IC 2391 was bimodal, in contrast to the observed distribution for the T Tauri stars. If a larger fraction of the IC 2391

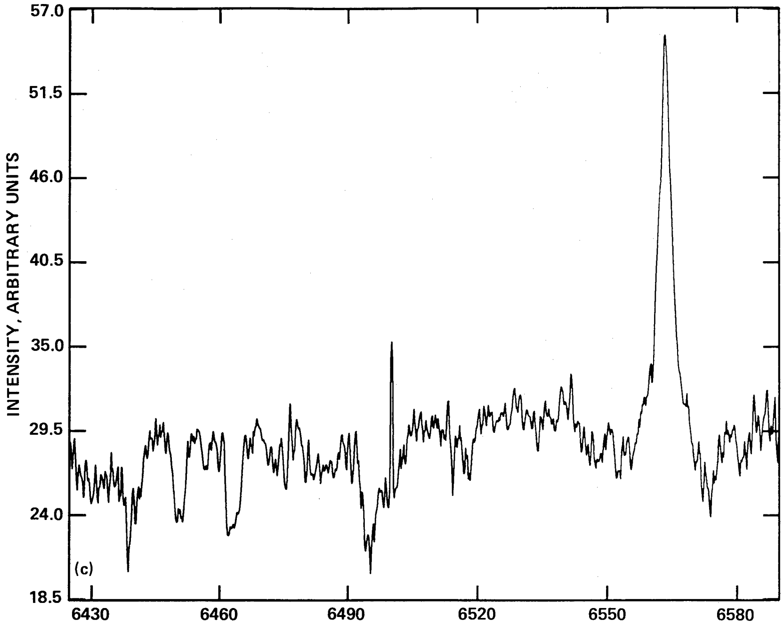

FIG. 4*c*

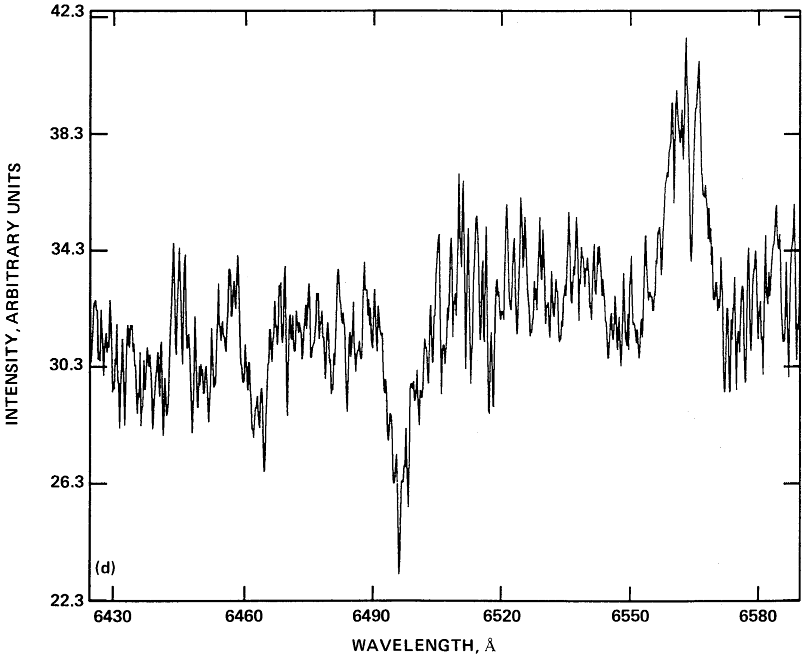

FIG. 4*d*

stars formed planets or have binary companions, the slow rotators might correspond to these stars. It will be illuminating to observe a richer cluster of similar age.

### *b) Pre–Main-Sequence Lithium Burning*

The large spread in inferred lithium abundances at a given effective temperature among late-type members of the Pleiades has been ascribed to an age spread of order $10^8$ yr (Duncan and Jones 1983; Butler *et al.* 1987). Butler *et al.* show a correlation between rotational velocity and lithium equivalent width, and assume that the dispersion in both properties is due to an age spread. For the IC 2391 sample, there is at most a small age spread but an appreciable rotational velocity spread. It would therefore be useful to examine quantitatively the lithium strengths for our stars as a function of rotation. Unfortunately, there are too few stars with detected lithium to make this a useful exercise. In particular, only one of the rapid rotators is early enough in spectral type to show detectable lithium.

The greater depletion of lithium in later type stars in the Pleiades and Hyades (Duncan and Jones 1983) is usually ascribed to the deeper convection zones of main sequence, lower mass stars bringing more lithium in the envelope down

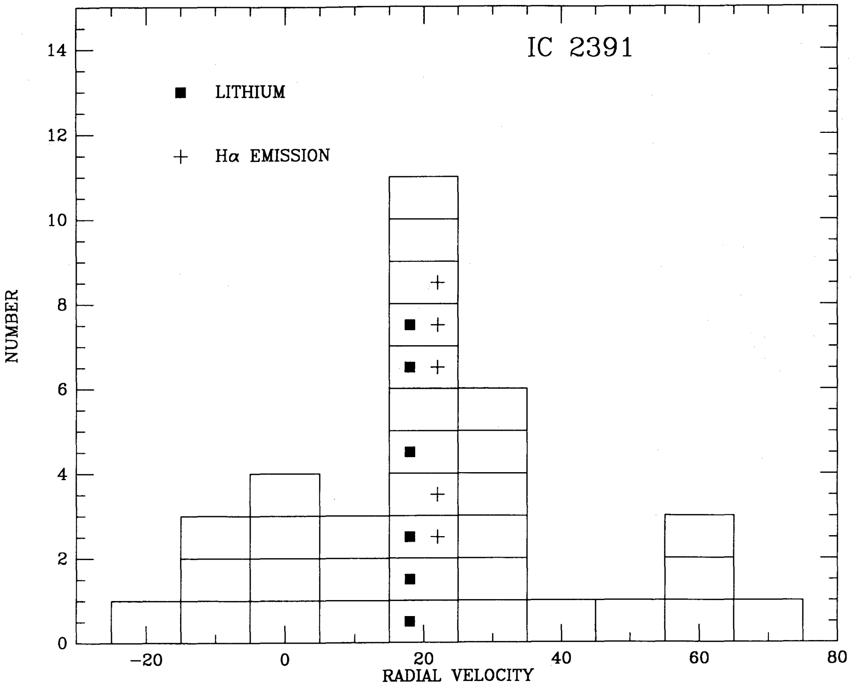

FIG. 5.—Histogram of radial velocities for stars toward IC 2391. The stars with Hα in emission or strong lithium absorption all have radial velocities consistent with cluster membership. Note that the zero point of our radial velocity system has not been set accurately and may be in error by several kilometres per second.

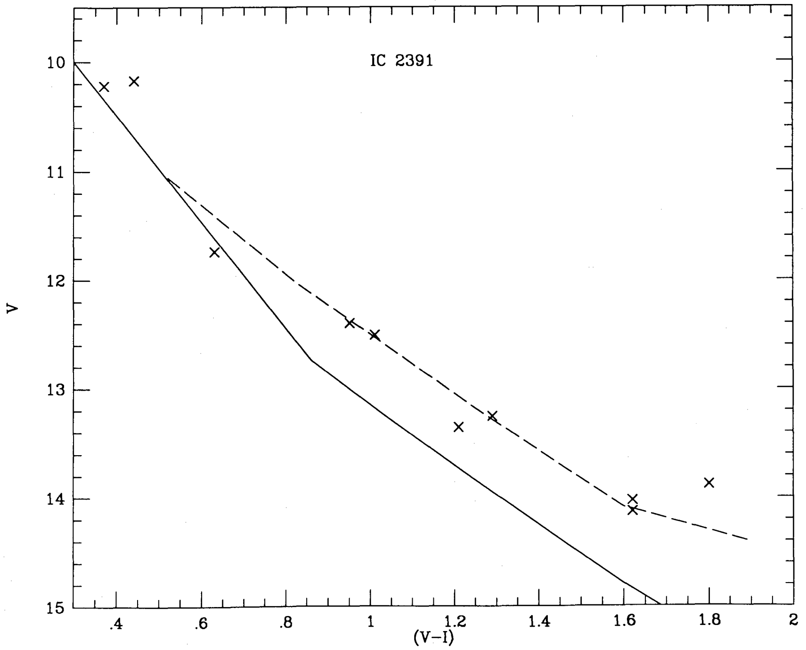

FIG. 6.—Color-magnitude diagram for just the stars identified as probable cluster members based on their radial velocities, lithium strength, Hα emission, and photometric properties. Solid curve is a fit to the lower envelope of the Pleiades members (shifted to the IC 2391 distance modulus), and the dashed curve is a $3 \times 10^7$ yr isochrone from VandenBerg (1987). A reddening correction of $A_V = 0.12$ mag has been applied to the photometry.

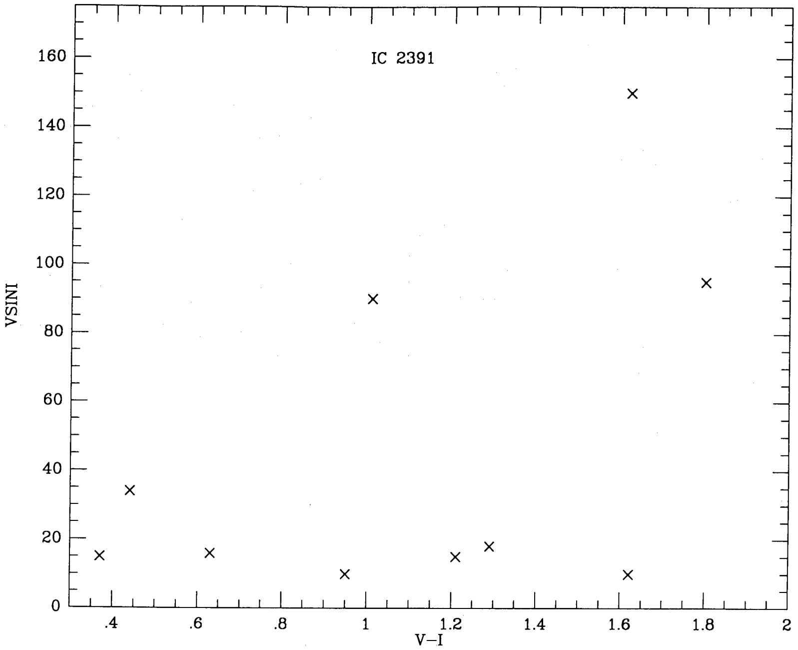

FIG. 7.—Rotational velocity distribution for the proposed late-type members of IC 2391. Some of the points with $v \sin i < 20$ km s$^{-1}$ are only rotational velocity limits.

to where temperatures are high enough for lithium burning. That explanation is not valid for the IC 2391 stars later than mid-G because they have not yet reached the main sequence. Some of the lithium depletion observed for the Pleiades stars is believed due to pre–main-sequence lithium burning (allowed by the much deeper convective envelopes during PMS evolution), as predicted by Bodenheimer (1965). Because all of the IC 2391 stars studied here are either pre–main-sequence or have just arrived on the main sequence, the IC 2391 stars provide the first definitive test for the extent of PMS lithium burning.

Figure 8*a* shows lithium abundances for the IC 2391 stars; Figure 8*b* shows Pleiades lithium data at the same scale for comparison purposes (Duncan and Jones 1983; Butler *et al.* 1987). Temperatures for the IC 2391 stars were derived using calibrations provided by Duncan and Jones (1983), Veeder (1974), and Mould and Hyland (1976). The curves of growth provided by Duncan and Jones were used to derive the abundances. Several stars have temperatures cooler than Duncan and Jones's coolest model ($T = 4500$ K). For the purposes of producing Figure 8*a*, we have simply used the 4500 K curve of growth for our $T < 4500$ K stars; using a model for the correct temperature would yield a lower abundance. Thus the coolest stars in the figure are marked as measured upper limits (where we did detect lithium) and simply as limits where the lithium line was not detected. The precise lithium abundances for these stars are not crucial—the important point is that their outer convective zones have quite small lithium abundances.

The small number of stars for which we can derive lithium abundances in IC 2391 prevents us from making absolute statements. However, two conclusions seem well documented by even the present data. First, PMS lithium burning is significant for low-mass stars. Bodenheimer's model appears to predict too much PMS burning for approximately solar mass stars, but the shape of the relationship is correct. Given the difficulty of the calculations, the model appears to match the observations remarkably well. Second, because the locus of the IC 2391 lithium abundances falls below many of the Pleiades stars, a significant portion of the spread in lithium abundance observed in the Pleiades must be due to something other than age differences. That is, all of the Pleiades stars in Figure 8*b* are known to be older than the IC 2391 stars because they (the Pleiades stars) are on the main sequence. The existence of Pleiades stars with considerably more lithium than the IC 2391 lithium locus must therefore indicate either that PMS lithium burning is a function of some additional parameter other than age and mass, or that the apparent lithium abundances/effective temperatures are in error due to peculiarities in the stars (e.g., spottedness), duplicity, or errors in the observations. Only the points below the IC 2391 lithium locus can be used to derive an age spread estimate for the Pleiades from main-sequence lithium burning. Most of the lithium dispersion in the Pleiades is thus due to non–age-related factors, indicating that the possible age spread among low-mass stars in the Pleiades is considerably smaller than had been estimated previously.

The Butler *et al.* (1987) stars should be useful laboratories to attempt to identify the cause of the lithium spread in the Pleiades. The four slowly rotating stars in their sample appear to have lithium abundances compatible with that expected from PMS lithium burning. The four lithium-rich, rapidly rotating stars are not extremely young (i.e., < 70 Myr) because they all lie, within the errors, on the single-star, zero-age main sequence (ZAMS) (SH87). Therefore, their enhanced lithium equivalent widths are most likely due to (1) peculiarities in their photospheres (Giampapa 1984) enhancing the lithium line strengths without necessarily indicating enhanced lithium abundance; or (2) less efficient PMS lithium burning. The rapid rotators are more spotted than the slowly rotating stars of the same effective temperature (Stauffer 1984), providing some evidence in favor of the first option. A reasonable expectation of this option is that the lithium strength should vary with time because these stars have highly asymmetric spot

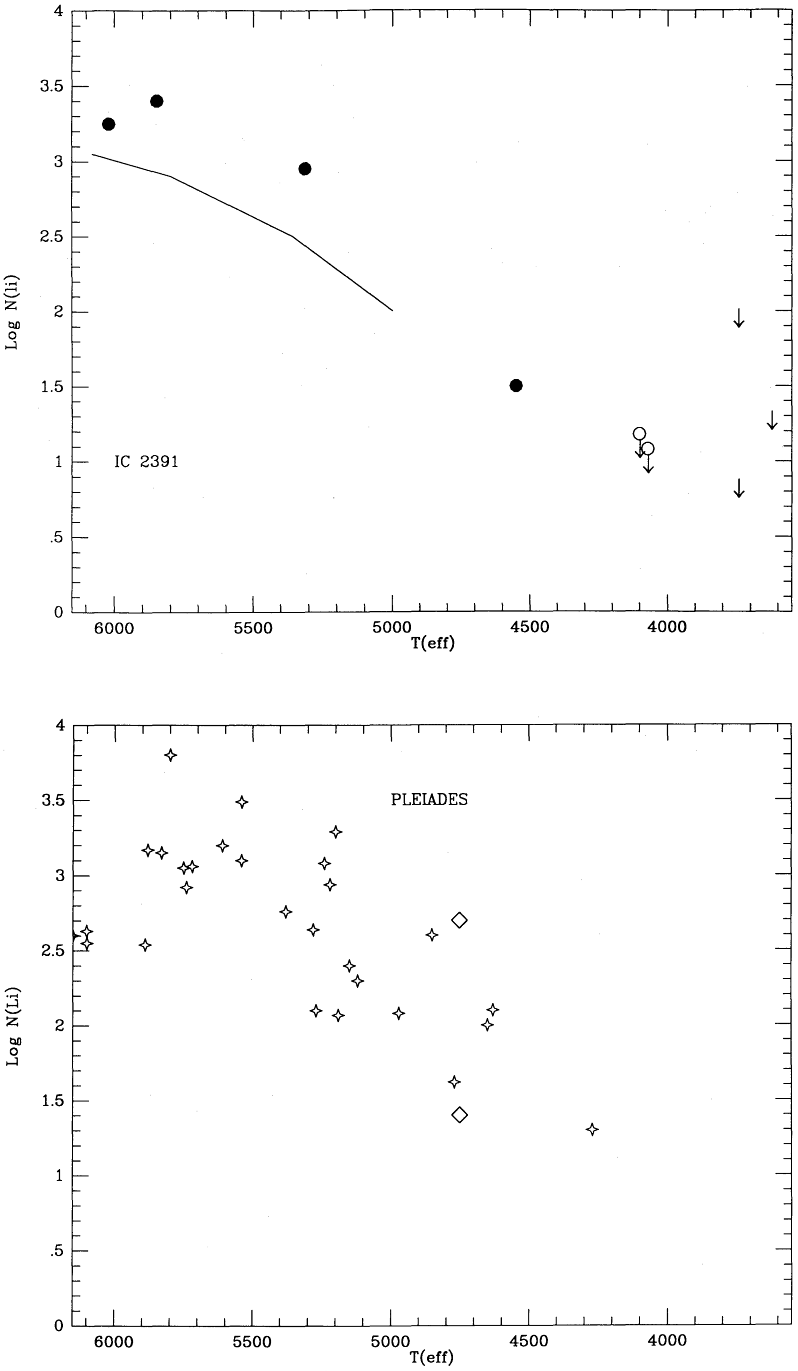

FIG. 8.—(*a*) Lithium abundances for the IC 2391 stars. See the text for an explanation of how the lithium abundances (and limits) were derived. The curve is the pre–main-sequence lithium burning prediction of Bodenheimer, as shown in Fig. 5 of Duncan and Jones (1983). (*b*) Lithium abundance vs. effective temperature for late-type members of the Pleiades. Crosses represent data from Duncan and Jones (1983), while the diamonds are averages of the four slow and four rapid rotators from Butler *et al.* (1987).

distributions and variable light curves (Stauffer *et al.* 1987). Very precise repeated observations of heavily spotted, bright nearby stars (Boesgaard 1987; Giampapa 1987), however, have failed to detect any phase-dependent variations in lithium equivalent widths, thus making it difficult to use this mechanism to explain the Butler *et al.* results.

Pre–main-sequence lithium burning for the rapid rotators might be decreased due to the slightly lower internal temperatures expected for these stars compared to the slow rotators. The predicted amount of pre–main-sequence lithium depletion for the outer convective envelopes of low-mass stars is an extremely sensitive function of the opacities assumed, mixing length theory, the rate at which the bottom of the convective envelope recedes from the core, and the temperature at the bottom of the convective envelope. Stringfellow, Swenson, and Faulkner (1987) have shown that just increasing the interior opacities by 50% over that used by Bodenheimer (an increase which they consider plausible) leads to considerably more PMS lithium burning than predicted by Bodenheimer, enough in fact to entirely explain the lithium depletion observed in Hyades G and K dwarfs without recourse to any main-sequence depletion of lithium in the outer convective envelope. At least potentially, then, small changes in other parameters could also alter the predicted lithium depletions. If the rotational velocity distribution is already bimodal when the PMS stars are near the bottom of the Hayashi track, and if rapid rotation does lead to a lower temperature at the base of the outer convective envelope, then perhaps rotation could provide the explanation for the observed lithium rotation correlation.

## IV. CONCLUSIONS

We have identified seven or eight new, late-type members of the poor open cluster IC 2391, and confirmed membership for two other stars previously suggested as possible members. The late-type stars fall above the ZAMS, approximately along a theoretical isochrone appropriate for the nominal age of the cluster ($3 \times 10^7$ yr). Three of the late-type members are rapid rotators with $v \sin i > 90$ km s$^{-1}$; the other stars observed all are slow rotators ($v \sin i < 35$ km s$^{-1}$). The rapid rotators all have H$\alpha$ in emission, with the emission-line profile broader than that due to just rotation alone—suggestive that some of the emission is formed in a wind.

The small number of stars identified in IC 2391 makes it difficult to formulate strong conclusions regarding angular momentum loss rates or lithium depletion during PMS evolution. However, the observations do demonstrate the power of observing a cluster of approximately this age. Because the stars in such a cluster should lie considerably above the main sequence, photometric observations can place strong limits on the age spread of the stars observed. Any remaining dispersion in observed properties of the stars must then be due to something else. By obtaining similar data for a cluster richer than IC 2391 it should be possible to successfully complete such a test.

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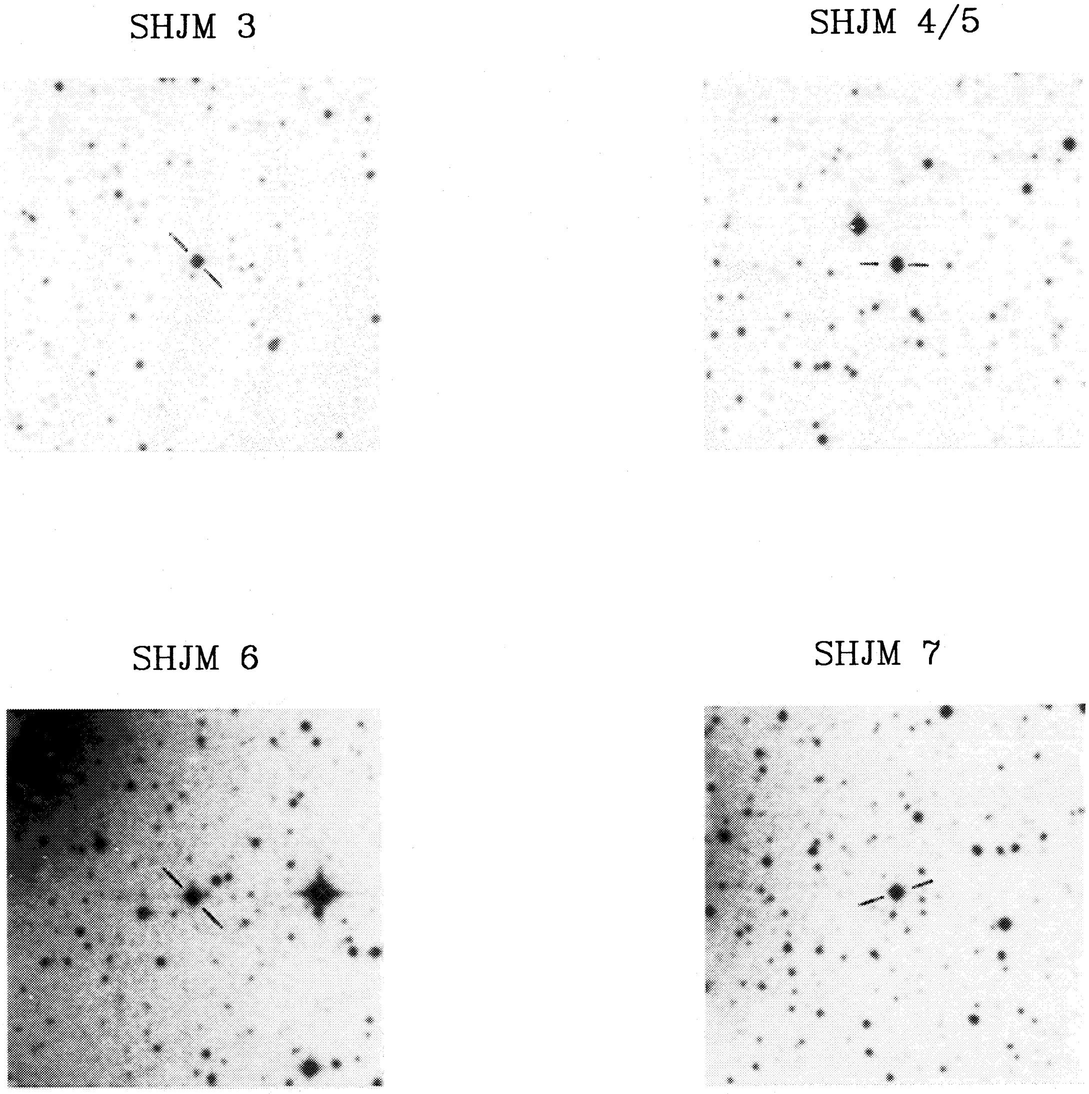

FIG. 3.—Finding charts for the new proposed members of IC 2391. The size of each of the boxes is ~4$'$.2 × 4$'$.2. North is up, east is to the left.

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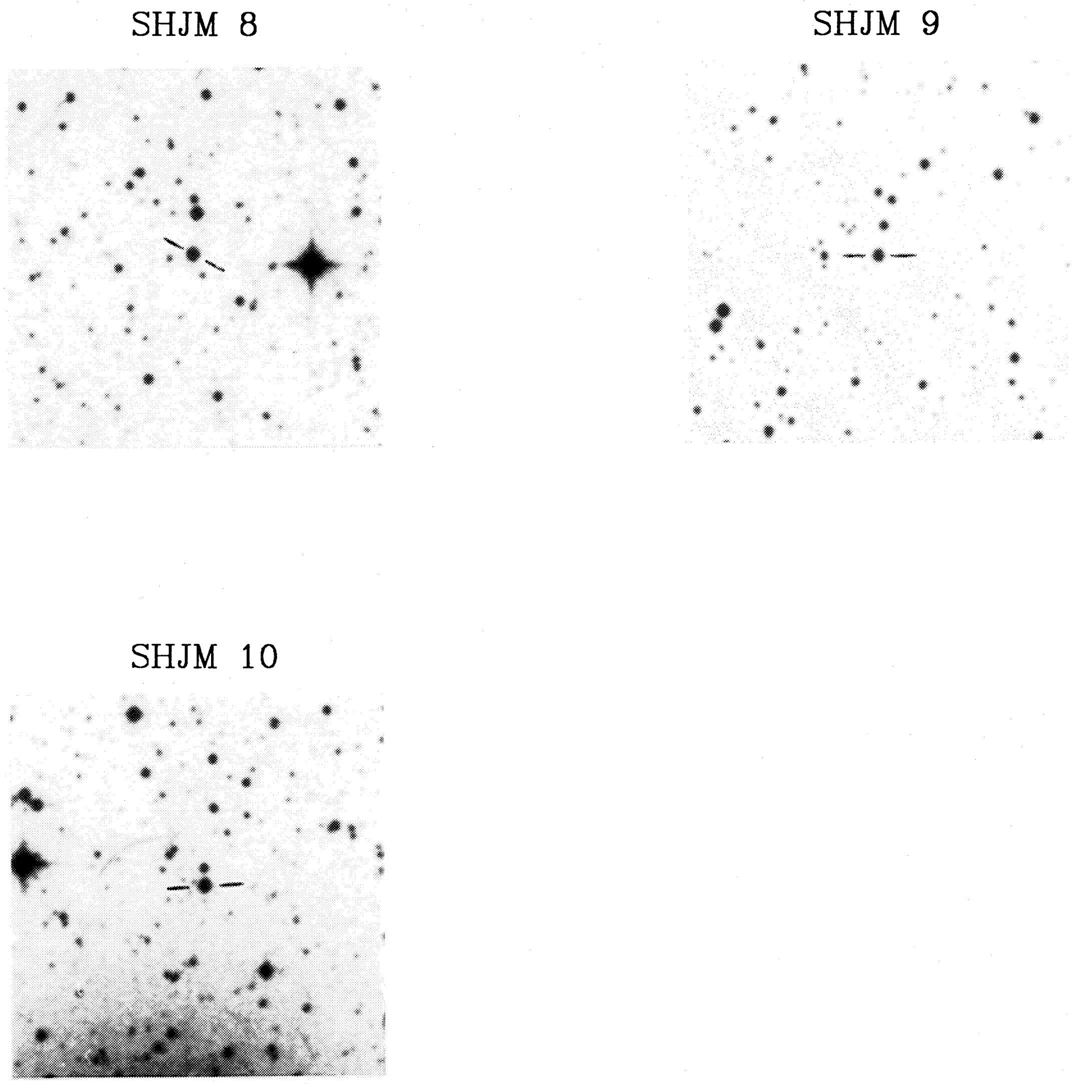

SHJM 8

SHJM 9

SHJM 10

FIG. 3.—*Continued*

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