Contracting Members of Double Stars

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Introduction

Stars which are so young that they are still contracting and have not yet reached the main sequence are called pre-main-sequence stars or pms stars. Observationally it is possible to distinguish between several categories of pms stars representing different kinds of stars and phases of evolution. An important and very well observed (though not well understood) group of such stars are the T-Tauri stars. They are generally found close to the interstellar clouds in which they were born, and compared to normal older stars they exhibit several peculiarities such as: irregular light variations, strong emission lines, high lithium abundance and excess emission both at ultraviolet and infrared wavelengths. If one determines the luminosities and surface temperatures for T-Tauri stars and plots them in an HR-diagram (such as Fig. 1) one finds that they occupy a region well above the main sequence. This location coincides with theoretical evolutionary tracks for contracting stars with masses of about 1 solar mass, calculated by Iben. Iben's models which are the ones which best agree with the latest observations of pms stars also show that the T-Tauri are younger than a few million years. Because their masses appear to be about that of the sun we identify the T-Tauri stars as the progenitors of solar-type stars.

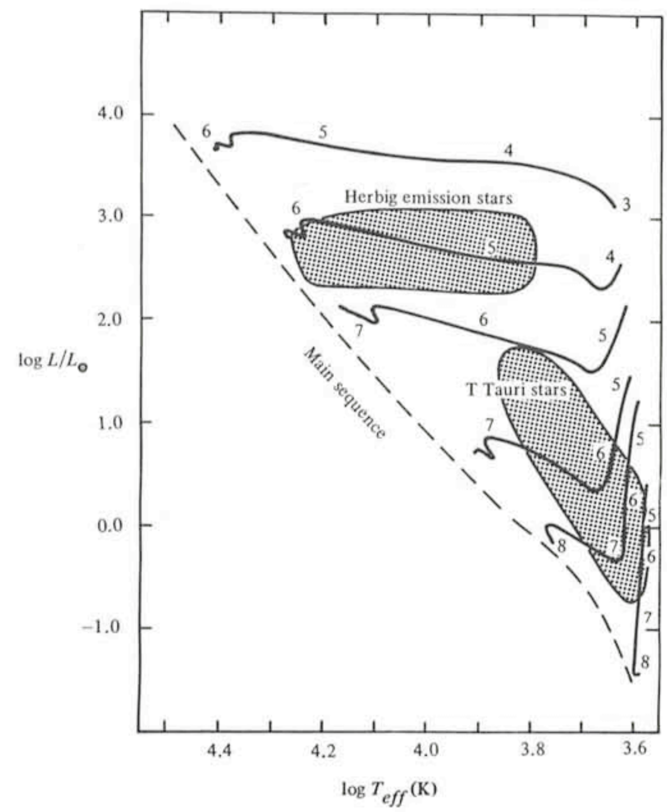

Fig. 1: *Evolutionary tracks in the HR diagram for theoretical models of stars contracting towards the ZAMS calculated by Iben. From bottom to top the tracks are for models with masses of 0.5, 1, 1.5, 3, 5 and 9 solar masses. Numbers along the tracks indicate the logarithm of the age at that point. The shaded areas show the location of two types of pre-main-sequence stars, the high-mass Herbig emission stars and the low-mass T-Tauri stars. (From Frontiers of Astrophysics, Harvard University Press.)*

The mass and age for pms stars can only be determined as above by comparing with the theoretical models, and the uncertainties in the derived values for individual stars are large. The reasons for this are several: the distances to these stars are not well known, so the luminosities are uncertain; the effective temperatures are uncertain; the models themselves are idealized and the position in the HR diagram of the evolutionary tracks and isochrones depend on the chosen chemical composition and mixing length parameter, etc. It is one of the aims of this investigation to test the theoretical isochrones by determining the ages of pms stars in an independent way and circumventing the other difficulties.

The Programme

Since the stars are born in interstellar clouds it is natural that the youngest are found (and searched for) in or close to nebulae. Many young stars are also found in the general star field, however. Obvious examples of such stars are hot main-sequence stars of spectral type B, which, as we shall see below, only have lifetimes of a few million to 300 million years. In general we do of course expect even the young field stars to be somewhat older and more evolved than stars associated with nebulae and therefore it is likely that the youngest solar-type stars we find there have already evolved through the T-Tauri phase. If so, the peculiarities by which they are identified as pms stars would be less pronounced or even absent and their discovery very difficult. Nevertheless, the main goal of this programme has been to detect such stars and to investigate their properties.

To achieve this goal a very special type of stars was selected as pms candidates. The candidates are faint secondary components of visual double stars with primary components of spectral type B. The reasons for this choice were the following: The rate of stellar evolution is very sensitive to the mass. The more massive a star is the more rapid its evolution and the shorter its life. A one-solar-mass star spends about 50 million years on its way down to the ZAMS and then stays 10 billion years at the main-sequence. For a nine-solar-mass star the corresponding numbers are 1 million years and 20 million years respectively. The whole life of a massive star can thus be shorter than the contraction time for a low-mass star. From this it is clear that all massive main-sequence stars that are observed on the sky must be of fairly recent origin. Suppose now that a double star is formed with one component (the primary) much more massive than the other (the secondary). If the mass difference is large enough the primary will reach the main-sequence while the secondary is still in the phase of contraction. If the masses differ by more than a factor of about 7 both stars will actually never be simultaneously at the main-sequence because then the primary's lifetime is shorter than the secondary's contraction time. Table 1 shows examples of such pairs and also lifetimes and contraction times for different stellar masses. If we require the primary to be a B-type star on the main sequence the chances are high that the double-star system is so young that a low-mass companion is still contracting or has just reached the ZAMS.

Guided by these considerations, more than 250 visual double stars with B-type primaries were selected for a spectroscopic and photometric survey. Figures 2 and 3 show how the systems are distributed over separation and magnitude difference. To ensure that the secondaries would be solar-type

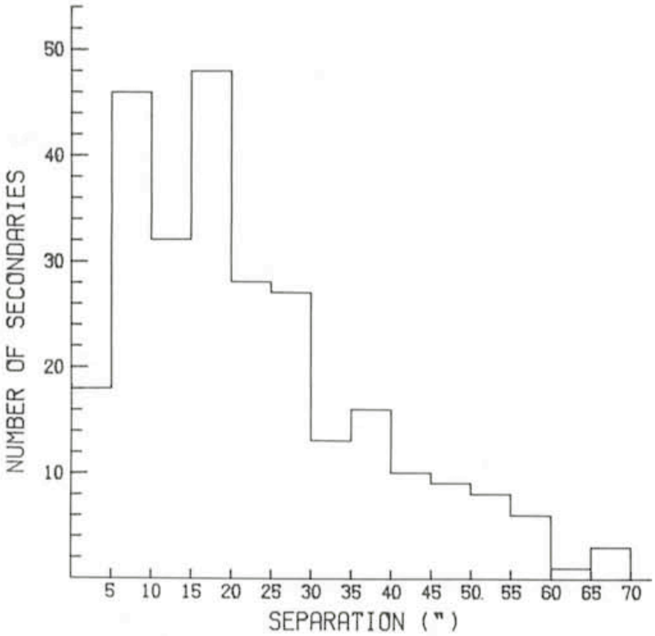

Fig. 2: *The distribution of the components separation. To avoid likely optical systems very few double stars with separations larger than 60" were included.*

stars rather close to the main sequence we also favoured systems with large magnitude differences. Most of the observations have been conducted at ESO, La Silla, with the following telescopes: Danish 50-cm, ESO 50-cm, 1-m and 1.52-m. The author has conducted the photometric part and Dr. Gahm the spectroscopic part of the programme.

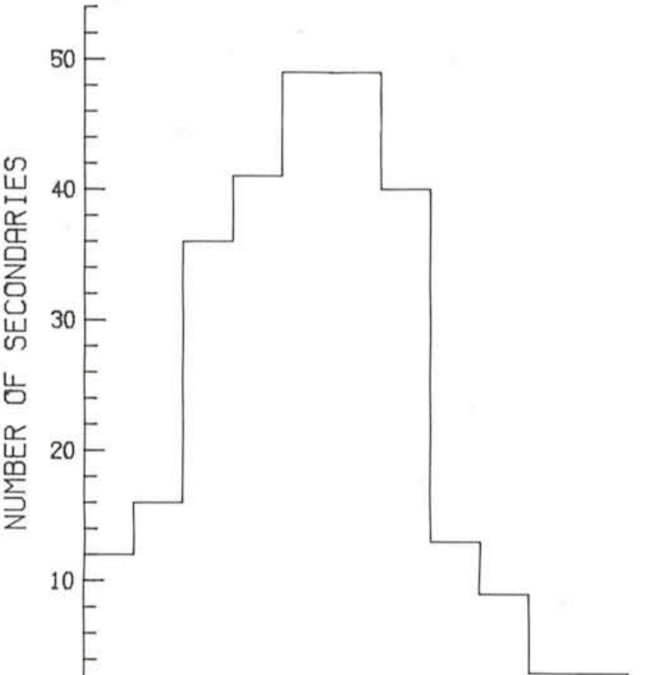

Fig. 3: *The distribution of the components magnitude difference. The small numer of systems with nearly equal brightness is due to the fact that we favoured large magnitude differences in order to find low-mass secondaries.*

The Primaries

As was discussed above, double stars with B-type primaries were selected to ensure that the stars were young. However, B-type stars also offer some other advantages: Many are bright on the sky which makes the observations easy and of high quality. Furthermore, from uvbyβ photometry it is possible to determine several important parameters such as interstellar reddening, effective temperatures and absolute magnitudes. These are in turn used for deriving the distance and age of the star. The primaries are very important in this investigation since it is from them that the distance and age of the secondaries are obtained. To derive the age (and also the mass) of the primary we employed the evolutionary tracks and isochrones calculated recently by Hejlesen for main-sequence stars leaving the ZAMS. From Fig. 4, which shows the positions of our primaries relative to the isochrones, it can be seen that almost all are younger than 200 million years and that many are younger than the contraction times of solar-type stars.

The Secondaries

Double stars are very common phenomena. The sun is actually rather unique in being a single star. Despite this, many of the double stars seen on the sky are optical pairs where two stars just happen to lie along the same line of sight as seen from

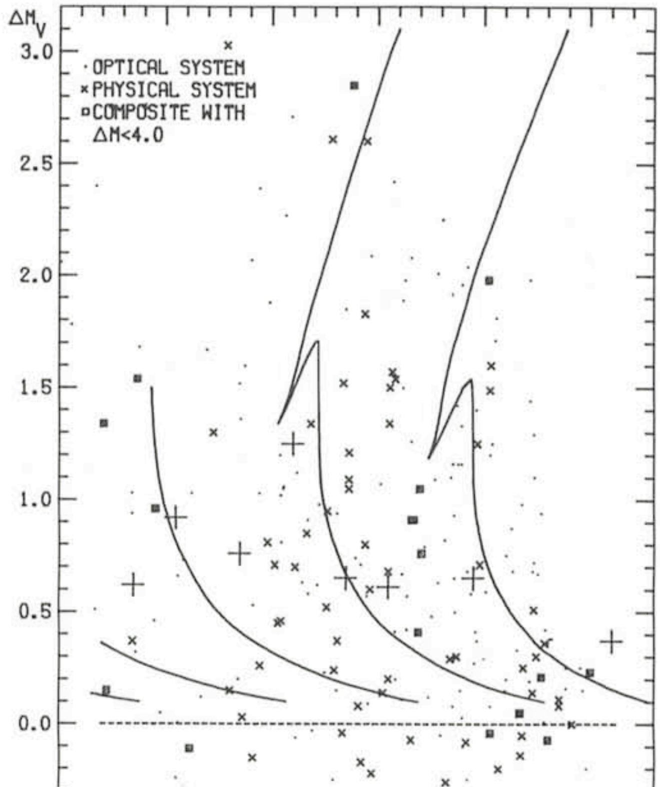

Fig. 4: *The positions of the primaries relative to the isochrones calculated by Hejlesen for model stars leaving the ZAMS. The isochrones are, from left to right, for ages of 1, 3, 10, 32 and 100 million years. The ZAMS is the dashed horizontal line. The horizontal scale is the surface temperature and the vertical scale is the difference in the absolute magnitude between the star and the ZAMS. As a star evolves from the ZAMS its brightness increases while the surface temperature decreases. The large "+" signs indicate the average positions of main-sequence stars.*

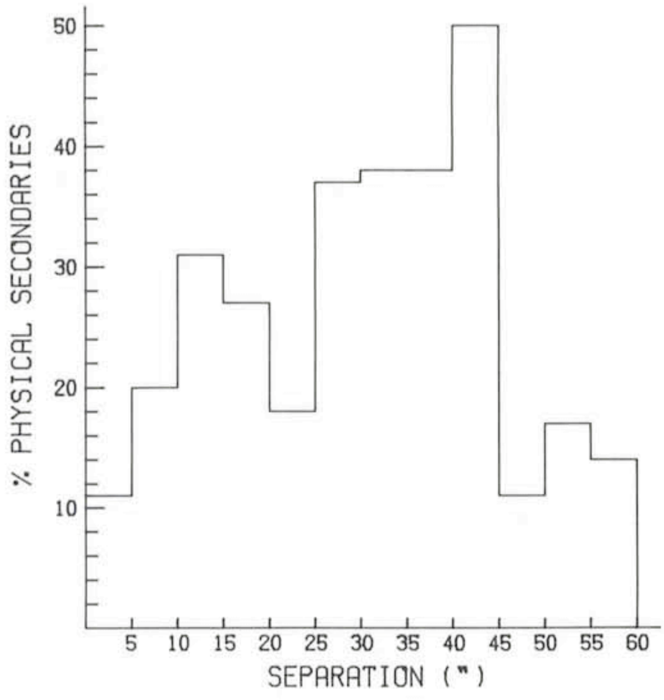

Fig. 5: *The fraction of physical double stars in different intervals of separation. It is surprising that the percentage of physical systems decreases rather than increases towards smaller separation.*

the earth. Optical pairs are of course uninteresting for our investigation and their inclusion could lead to erroneous results. The probability that a double star is optical increases with separation and magnitude difference between the components. In order to exclude systems which very likely are optical we concentrated our study to systems with separations less than 60″. Yet, because of the large magnitude differences many of the systems must be optical and therefore the first step in the analysis of the secondaries was to identify those and reject them from the remaining investigation. To decide if a pair is optical several criteria were used and a system was classified as optical if one of them was fulfilled. The criteria used can be summarized as follows: the components have different radial velocity, they have different interstellar reddening, the secondary is too faint or bright to be at the same distance as the primary.

These criteria proved to be very powerful. Only 70 secondaries or 26% were retained as physical companions. The majority of them are of spectral types F, G or K, so we succeeded in identifying young low-mass stars. The percentage of physical secondaries in different separation intervals is shown in Fig. 5. It turns out that the fraction of physical pairs is very small not only for the larger separations but also for the smaller ones, say less than 10″. The latter is remarkable since it is naturally expected and also observed for double stars in general that the frequency of physical pairs strongly increases with decreasing separation. This unexpected result may reflect how the true separations for systems like these are distributed. Small apparent separations in general also means small true separations and it therefore appears that systems like ours, i.e. with large mass difference, have large orbits. An intuitive explanation of this is that the massive primary which evolves much more quickly to the ZAMS disturbs the surrounding medium so much that the formation of low-mass companions is prevented within a certain radius. The decline of physical pairs sets in at an apparent separation of about 10″ which at the typical distances of these stars corresponds to a projected separation of a few thousand astronomical units. Support for

Table 1. Double stars for which the primary's lifetime at the main sequence (t_{ms}) equals the secondary's contraction time to the ZAMS.

Primary			Secondary	
Sp	Mass	t_{ms}	Mass	Sp
07	30	4.90×10^6	2.5	B7
09	15	1.04×10^7	2.0	A0
B0.5	9	2.21×10^7	1.3	F0
B2	5	6.68×10^7	0.9	G5
B5	3	2.42×10^8	0.4	M0

this explanation also comes from the distribution of the physical systems over the projected separation, Fig. 6. The number of systems first increases as expected towards smaller separation, then levels off and finally drops at separations below 1,000 A.U.

The projected separation is less than 15,000 A.U. for 90% of the systems. Statistically this corresponds to an orbit with a semimajor axis of less than 24,000 A.U. The orbits are generally quite large and even for the smaller ones the period of revolution is more than a thousand years and therefore it is unfortunately impossible to derive the masses of the stars by studying the orbital motion.

Contracting Secondaries

The members of a double star are most certainly born at the same time. Therefore the ages that we determined for the primaries also apply to secondaries. By comparing the theoretical contraction time to the ZAMS calculated by Iben for stars of different masses with the ages of our secondaries it was found that 38 were so young that they should not yet have reached the ZAMS. In the HR diagram we expect these contracting stars to fall above the ZAMS and as can be seen in Fig. 7 this is also the case. The typical height above the observed ZAMS for these stars is almost one magnitude compared to only 0.3 magnitude for the older ones. The spectral types for all the contracting secondaries are later than A0 and this means that 70 % of the late-type secondaries are contracting.

The ages and positions in the HR diagram for our stars can be compared with the isochrones calculated by Iben. The result is that all our secondaries more massive than one solar mass are several million years older than predicted by the isochrones. This indicates that the isochrones of the main-sequence models do not agree with those of the pre-main-sequence models. If we believe in the former models (after all main-sequence stars are better understood than pms stars) it means that the currently used contraction times are underestimated. In that case still more of our secondaries could be in the

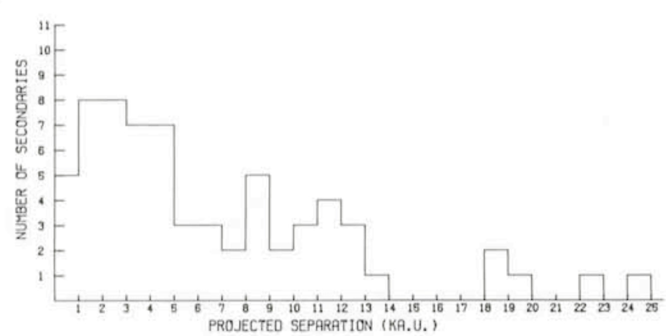

Fig. 6: *The distribution of the projected separations in units of 1,000 A.U.*

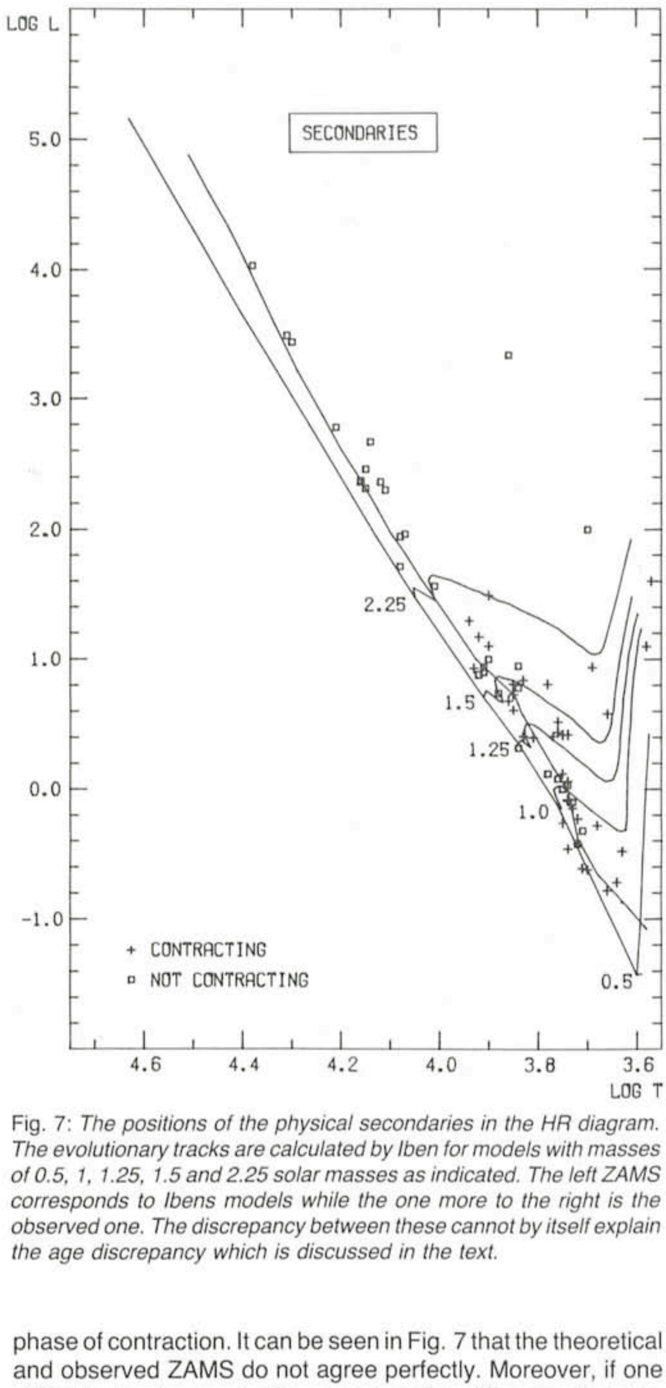

Fig. 7: *The positions of the physical secondaries in the HR diagram. The evolutionary tracks are calculated by Iben for models with masses of 0.5, 1, 1.25, 1.5 and 2.25 solar masses as indicated. The left ZAMS corresponds to Ibens models while the one more to the right is the observed one. The discrepancy between these cannot by itself explain the age discrepancy which is discussed in the text.*

phase of contraction. It can be seen in Fig. 7 that the theoretical and observed ZAMS do not agree perfectly. Moreover, if one shifts the isochrones by the corresponding difference in temperature the discrepancy still remains. As mentioned earlier, these pms star models are idealized, e.g. they do not take into account the effects of rotation while real pms stars are suspected to be fast rotators. It would be interesting to see if the isochrones from more elaborate models agree better with our results.

Peculiarities

Although many of the secondaries fall above the ZAMS they are closer to it and also older and more evolved than typical T-Tauri stars. None of them which have been spectroscopically investigated exhibit any strong T-Tauri characteristics and we conclude that the T-Tauri phase ends several million years before the stars settle on the ZAMS. This is also supported by the infrared results. Practically all of the contracting secondaries were measured in JHKL in order to detect any possible infrared excess emission which is common for T-Tauri stars. The presence of such excess emission is explained by a circumstellar dust cloud which is heated by the stellar radiation. Again, none of the investigated stars show any excess. Their JHKL magnitudes are those of normal stars of the same spectral type. The stars therefore seem to shed their circumstellar material at the end of the T-Tauri phase and they reach the ZAMS as quite normal stars.

Despite the fact that none of the secondaries show any strong pms characteristics, more than 25 % do exhibit some spectroscopic peculiarity. In particular emission lines of Hα and Ca H, K are frequent, and a strong absorption line of lithium at 6707 Å is present in the spectra of several contracting stars. A few stars also have very broad and diffuse spectral lines. All these features are common to pms stars and spectroscopically some of the secondaries resemble T-Tauri stars of the weakest emission class.

The primordial lithium is destroyed by protons while the stars are contracting and therefore the presence of a strong lithium line is important since it demonstrates that the stars are young. Unfortunately only a limited number of secondaries have so far been investigated in the red part of spectrum and it is therefore likely that the number of stars with Hα emission and strong Li absorption is much higher. However, in the material we have, it is interesting to note that all the contracting stars which have a Li line also have Ca H,K emission. This suspected coupling will be further investigated in May 1982 with the ESO 3.6-m telescope.

The first results of this investigation have been published as a thesis (Lindroos, *Stockholm Observatory Report* No. 18, 1981). The whole investigation will be presented in a series of articles in *Astronomy and Astrophysics.*

Visiting Astronomers

(April 1 – October 1, 1982)

Observing time has now been allocated for period 29 (April 1 – October 1, 1982). The demand for telescope time was again much greater than the time actually available.

The following list gives the names of the visiting astronomers, by telescope and in chronological order. The complete list, with dates, equipment and programme titles, is available from ESO-Garching.

3.6-m Telescope

April: Israel/de Graauw/van der Stadt, Eichendorf/Krautter, Eichendorf/Reipurth, Léna/Foy/Mariotti/Perrier, Krautter/Vogt/Beuermann/Ritter, Brahic, Kunth/Joubert, Audouze/Dennefeld, Lachieze-Rey/Vigroux.

May: Lachieze-Rey/Vigroux, Campbell/Pritcher, Cayrel G.+R., de Bruyn/van Groningen, Lindros/Gahm, Weigelt, Motch/Ilovaisky/Chevalier, Jörgensen/Norgaard-N., Tarenghi, Pakull.

June: Landini/Oliva/Salinari/Moorwood, Moorwood/Glass, Decanini/Fossat/Grec, Alcaíno, Fusi Pecci/Cacciari/Battistini/Buonanno/Corsi, Rosino/Ortolani, Seitter/Duerbeck, Häfner/Metz, Pedersen/Lewin/van Paradijs, Wargau/Drechsel, van der Hucht/Thé, Koornneef/Westerlund.

July: Koornneef/Westerlund, Nguyen-Q-Rieu/Epchtein, Kreysa/Mezger/Sherwood, Steppe/Witzel/Biermann, Schultz/Sherwood/Biermann/Witzel, Sherwood/Gemünd, Schnur, Fricke/Kollatschny/Biermann/Witzel, Adam, Ardeberg/Nissen, Danks/Wamsteker.

August: Danks/Wamsteker, Engels/Perrier, Chevalier/Ilovaisky/Motch/Hurley/Vedrenne, D'Odorico/Grosbøl/Rosa, Greenberg/Brosch/Grosbøl, Seggewiss/