VBLUW Photometry of OB Associations: SPECTER at La Silla

E. DE GEUS and J. LUB, Sterrewacht Leiden, the Netherlands
T. DE ZEEUW, Institute for Advanced Study, Princeton, USA

Introduction

A study of the nearby OB associations is necessary for a better understanding of the process of star formation. The most important reason for this is that in these associations the placental material out of which the observed stars formed is still present.

Of particular interest are differential age effects for spatially separate subgroups. This can reveal the sequence of star formation within the associations, and on a larger scale within the local spiral arm. Furthermore, there is the long-standing discrepancy between nuclear and kinematic ages. Finally age differences between stars of different mass but within the same subgroup might occur.

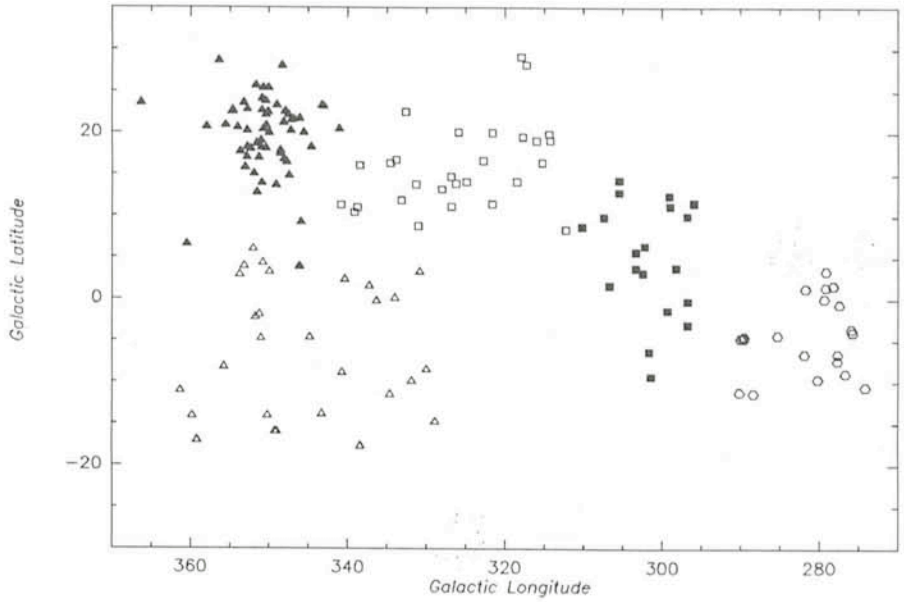


Figure 1: *Positions of the certain members of the subgroups of Sco OB2. △ : Subgroup 1; ▲ : Subgroup 2 (Upper Scorpius); □ : Subgroup 3 (Upper Centaurus Lupus); ■ : Subgroup 4 (Lower Centaurus-Crux); ○ : Subgroup 5.*

Studies of OB associations are severely hampered by poorly known membership. Membership determination via a colour-magnitude diagram is very inaccurate due to the large distance spread within an association. The large angular extent on the sky of most associations makes proper motion measurements difficult to compare because of problems connecting photographic plates with different plate centres. For these reasons a consortium called SPECTER has been formed at Leiden Observatory. It has been granted observing time on the HIPPARCOS satellite for measuring accurate proper motions of over ten thousand stars in the direction of the nearby associations. The results from HIPPARCOS will become available only after 1992. SPECTER will in the mean time gather a variety of other data relevant for the study of these associations. Amongst these are systematic investigations of the dust and gas components of the associations, spectroscopic studies to determine radial and rotational velocities of the stars, and extension of the available photometric data. We have nearly completed a large photometric programme at ESO with the Walraven photometer at the Dutch 91-cm telescope. The aim is to obtain homogeneous VBLUW colours for all southern HIPPARCOS programme stars. Here we present some preliminary results for Sco OB2 (or Scorpio-Centaurus) which is the nearest OB association.

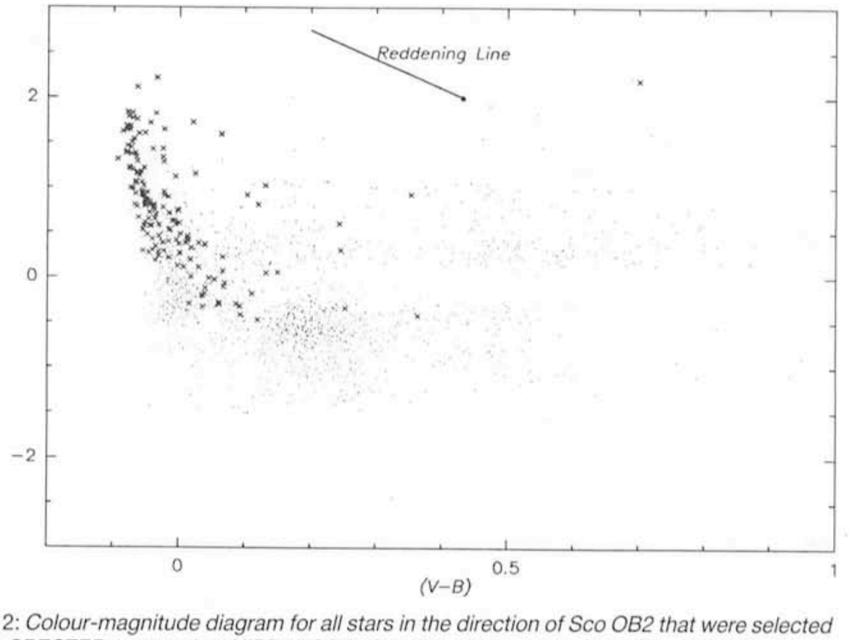
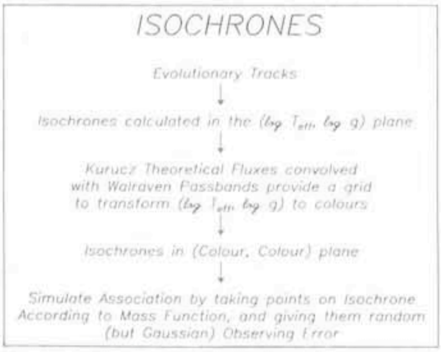


Figure 2: *Colour-magnitude diagram for all stars in the direction of Sco OB2 that were selected for the SPECTER proposal to HIPPARCOS. Certain members are denoted by crosses.*

The Programme Stars

One of the most beautiful constellations in the winter sky on the southern hemisphere is undoubtedly Scorpius. Passing right through the zenith it extends over some 15 degrees in the sky. The bright stars in Scorpius belong together also in the third and the fourth dimension. They form part of the Sco OB2 association. Blaauw (1964) subdivides Sco OB2 in 5 subgroups of which the three best known are Upper Scorpius. Upper Centaurus Lupus and Lower Centaurus Crux. Figure 1 shows their positions relative to one another. The runaway star: ζ Oph and the M supergiant Antares are members of the Upper Scorpius subgroup. The problems concerning membership determination are felt most in this association, especially if we compare the number of certain members to the total number of early-type stars in the region. The first members were found by Blaauw (1946),



Box 1.

using proper-motion data. Since then a study by Bertiau (1958) added members, based on proper motions, to the list for Upper Scorpius. As a result, membership is at this moment certain for stars down to only B5 for Upper Centaurus Lupus and Lower Centaurus Crux, and down to B9 for Upper Scorpius. For both Upper Scorpius and Upper Centaurus Lupus a number of additional probable members are known based on photometric data. In Figure 2 we show the Walraven V versus (V-B) diagram for all selected stars in the direction of Sco OB2. The certain members, denoted by crosses, do not form a clear thin strip in the colour-magnitude diagram, as is for instance seen in stellar clusters. This spread of the datapoints is due to the reddening caused by the patchy distribution of the interstellar clouds, as well as the considerable spread in the distances of the stars. So it is clear that colour-magnitude diagrams cannot be used directly to determine membership.

We selected our programme stars as candidate members for the HIPPARCOS project using the following criteria: spectral type (earlier than F8), apparent magnitude and location. For the three subgroups of Sco OB2 this leaves us with 4,000 programme stars of which 80 are known members (i.e. only 2%). It is of great importance to determine membership of Sco OB2 for stars of all spectral types: because the Sco OB2 association has a geometrically defined distance this would provide us with a means to determine the absolute magnitudes of stars over the whole range of effective temperatures, and thus to recalibrate the galactic distance scale. Another reason for the inclusion of stars of types later than A0 in the programme is that, since the ages of the three subgroups are small, we hope to find the turn-on point of the association. This would be of great significance for the knowledge of pre-main-sequence evolution of later-type stars and for an understanding of the Initial Mass Function.

Box 2. ▷

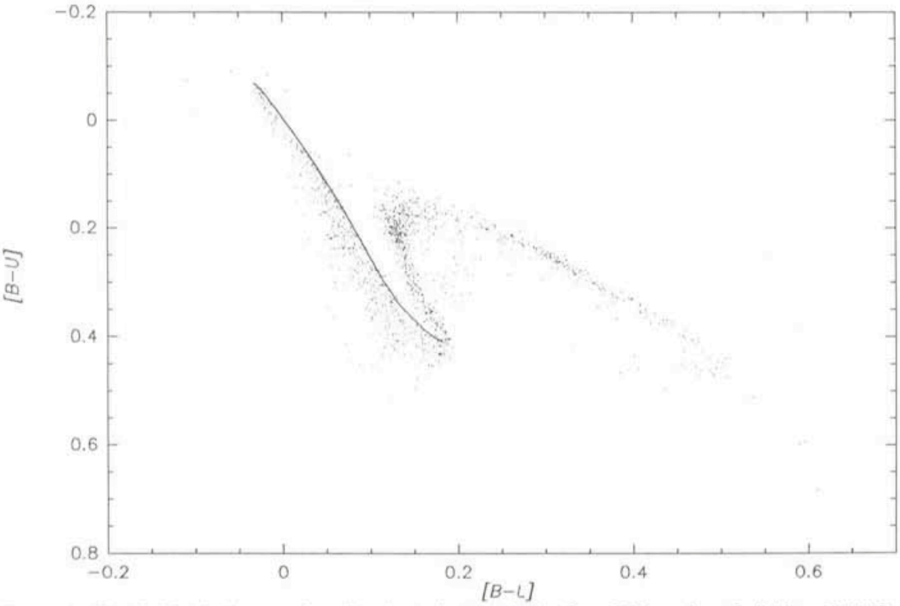


Figure 3: *([B-U], [B-L]) diagram for all selected stars in the Sco OB2 region. Solid line: ZAMS.*

Age Determination

Although the colour-magnitude diagrams cannot be used to reliably determine membership of the stars, the photometry can still be put to great use for the determination of other properties of the stars.

The age of an OB association can be determined based on the proper motions of the stars. Starting from the distribution of the stars at this moment one can calculate back, using the proper motions of the stars, the point in time that the stars filled the smallest volume. The resulting time gives one the so-called *kinematic age* (t_{kin}) of the association (Blaauw 1964). The other way to determine an age of an OB association is by comparing the loci of the stars in the HR diagram to theoretical isochrones, which results in the *nuclear age* (t_{nuc}). Earlier studies showed a discrepancy between the kinematic and nuclear ages (e.g. Blaauw 1964), with the former usually being significantly lower. Our objective is to find out, using the best data available, whether the discrepancy is real or just a result of for instance inaccuracies in the evolutionary models. A comparison of these two differently defined ages of an association is important. Since the process of disrupting the parent cloud is caused by the winds of the more massive stars, a large difference between t_{kin} and t_{nuc} implies formation of first the low mass stars and later the high mass stars. This is what one expects in cool parts of a molecular cloud. When t_{kin} and t_{nuc} are equal, high mass star formation occurs at more or less the same moment as low mass star formation, which is the case in hotter regions of a molecular cloud (Elmegreen and Lada 1977).

The isochrones we used were calculated from the evolutionary tracks of Maeder (1981) in the (log T_{eff}, log g) plane. The process is schematically represented in Box 1. A brief description of the Walraven photometric system is giv-

WALRAVEN PHOTOMETRY

The Walraven Photometer mounted on the Dutch 91cm Telescope at ESO La Silla measures the intensities in five bands (V,B,L,U and W) simultaneously. For the properties of the passbands we refer to Lub (1979).

In the Walraven system three independent reddening-free colours are defined by:

$$[B-U] = (B-U) - 0.61(V-B)$$
$$[U-W] = (U-W) - 0.45(V-B)$$
$$[B-L] = (B-L) - 0.39(V-B)$$

For OB-stars [U-W] and [B-L] are indicators of log g, and [B-U] is a measure for the Balmer jump and as such an indicator of T_{eff}

Note: V, B, L, U and W are ^{10}log(intensities), for standard Johnson colours:

$$V_J = 6.^{m}885 - 2.5(V + 0.0030(V-B))$$
$$(B-V)_J = 2.571(V-B) - 1.020(V-B)^2 + 0.500(V-B)^3 - 0.^{m}010$$

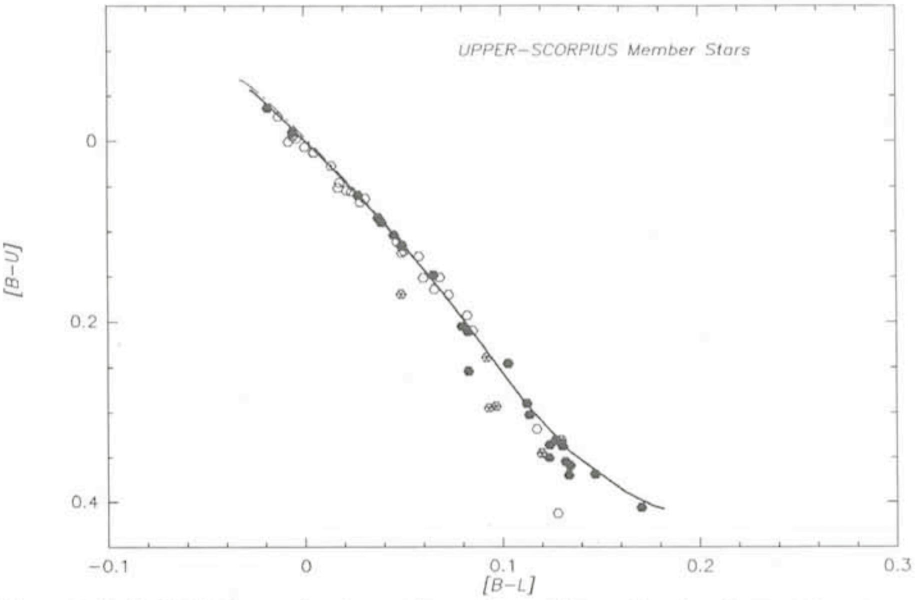


Figure 4: *([B-U], [B-L]) diagram for the certain members of Upper Scorpius. Fast rotating stars are denoted by filled symbols. Stars for which no rotational velocities are available are denoted by a cross. Dashed line: ZAMS. Solid line: best fitting isochrone (age: 4.5 million years).*

en in Box 2. In Figure 3 we show the [B-U] vs. [B-L] diagram for all selected stars in the Sco OB2 region together with the Zero Age Main Sequence. The ZAMS is clearly the envelope of the data which is precisely as it should be. Figures 4, 5 and 6 show the [B-U] vs. [B-L] diagrams of the three main subgroups of Sco OB2 together with the ZAMS and the best fitting isochrone. Note the difference between the amount of members in Upper Scorpius and in the two other subgroups.

Several stars do not lie on the isochrone, but systematically below it. We suspect that this is due to the effects that stellar rotation has on the colours. A rotating star will at the equator have a lower T_{eff} and log g than at the poles. This results in a difference between the observed colours when the star is looked at pole-on, and when looked at equator-on. Model calculations by Collins and Sonneborn (1977) showed that the effect of rotation on the colours in the Strömgren system can be large, depending on both v_e (rotational velocity at the equator) and the inclination angle i. The systematic scatter which results is substantial and if not corrected for will cause an overestimate of the age (De Zeeuw and Brand 1985). In Figures 4, 5 and 6 we denoted the fast rotating stars by filled symbols (v_e sin i > 160 km/s). We see that the fast rotators are in general shifted away from the Main Sequence more than the slow rotators. Especially in Upper Scorpius some fainter members do not have measurements of their rotational velocity; these are denoted by crosses.

We see no evidence for a relation between stellar mass and age, because taking into account the effects of rotation and duplicity all data are consistent with one isochrone. Doom et al. (1985) have found the contrary based on data of two rather younger OB associations. It is of great importance to check if their result is in any way an artifact of poor membership determination or of the neglect of stellar rotation.

Taking all these problems into account we find a nuclear age for each of the three main subgroups of Sco OB2. The results are summarized in the table. The uncertainty is mainly due to the effect of stellar rotation. As a comparison we also added the kinematic age of Upper Scorpius (Blaauw 1978). For the two other subgroups no kinematic ages have been determined.

Discussion

We have used the most accurate data available at present to determine the ages of the three main subgroups of Sco OB2. The discrepancy between the kinematic and nuclear age of Upper Scorpius is no longer present, and was apparently due to the inaccuracy of the evolutionary calculations used in earlier nuclear age determinations. The nuclear age is within the boundaries of the uncertainty equal to the kinematic age. The nuclear age being equal to the kinematic age implies that the moment the stars arrived on the Main Sequence more or less coincided with the moment the stars became gravitationally unbound. It would be interesting to measure the kinematic ages for the other subgroups and for other associations as well, which is one of the reasons why these stars were proposed to be measured by HIPPARCOS. Nuclear age determinations of other OB associations will enable us to make a statistically more reliable comparison between nuclear and kinematic ages.

The uncertainty in the ages is substantially reduced when we consider relative ages instead of absolute ages. In fact, for the problem of the star-forming sequence in an OB association the relative ages provide sufficient information. For the Sco OB2 association the idea of a wave of star formation sweeping through the molecular cloud is not valid, because the oldest subgroup Upper

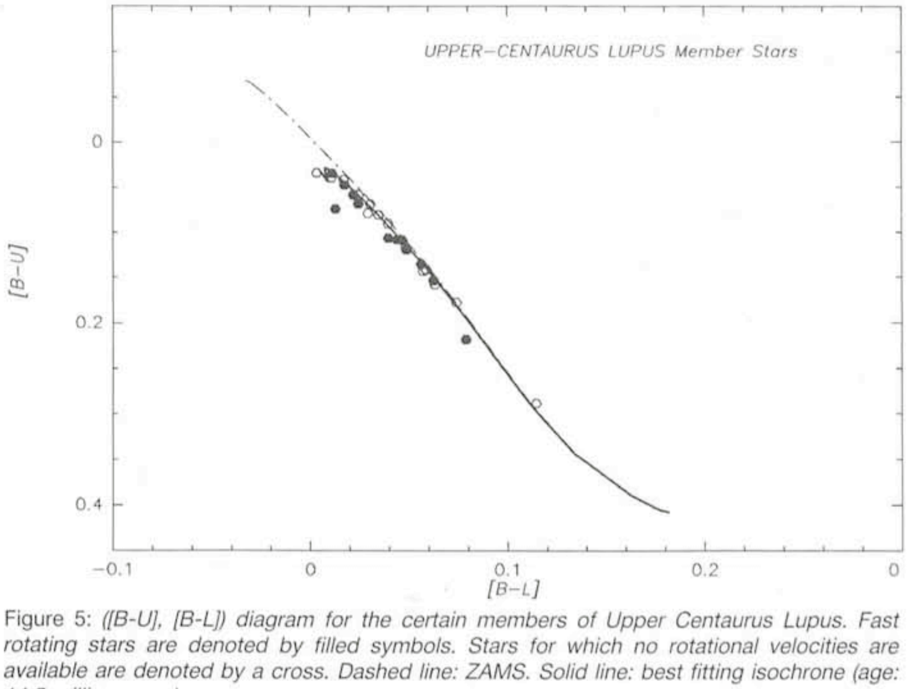


Figure 5: *([B-U], [B-L]) diagram for the certain members of Upper Centaurus Lupus. Fast rotating stars are denoted by filled symbols. Stars for which no rotational velocities are available are denoted by a cross. Dashed line: ZAMS. Solid line: best fitting isochrone (age: 14.5 million years).*

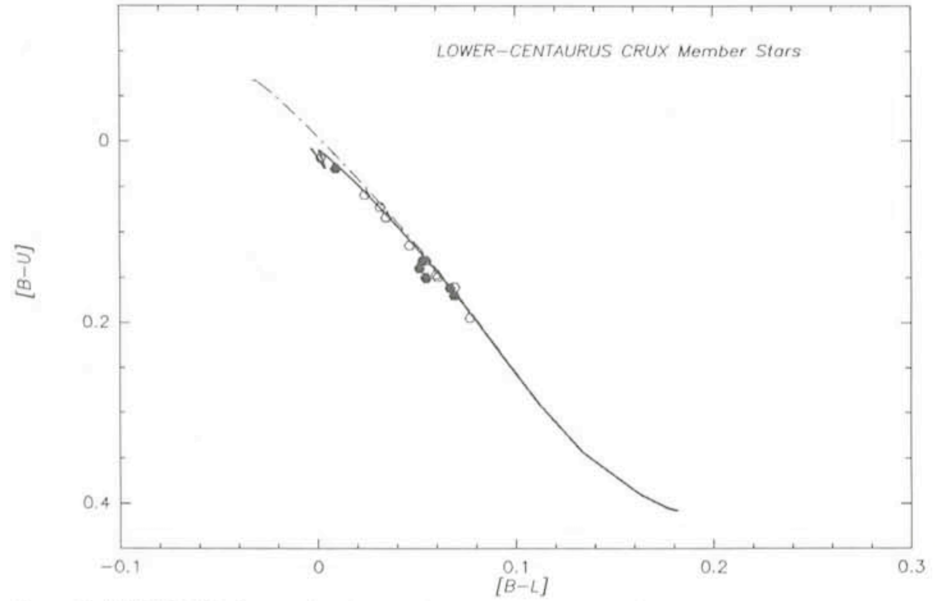


Figure 6: *([B-U], [B-L]) diagram for the certain members of Lower Centaurus Crux. Fast rotating stars are denoted by filled symbols. Stars for which no rotational velocities are available are denoted by a cross. Dashed line: ZAMS. Solid line: best fitting isochrone (age: 11.5 million years).*

Centaurus Lupus is positioned between the two younger ones. This however does not contradict the idea that star formation in the two younger subgroups was ignited by the propagating ionization front driven into the molecular cloud by the Lyman continuum radiation of the stars in Upper Centaurus Lupus.

Future Work

First of all we want to determine the effect of stellar rotation on the observed colours in the Walraven photometric system. This can be done in a similar way as Collins and Sonneborn (1977) have done for the Strömgren system. By simulating measurements of a group of stars, in which the effect of rotation is included, we can quantitatively determine the effect of rotation on the age determination.

Secondly we want to determine both radial and rotational velocities for the early-type stars. Radial velocities together with the proper motions of the stars will give us the space motions of the stars, which is first of all an accurate way to determine membership, but in the second place also a more accurate way to determine the kinematic age than from proper motions alone. The rotational velocities will be used to try to correct the age determinations for the effects of the rotation.

In the third place we want to study the interstellar medium of the OB associations. Most of the young associations still possess remnants of their parent molecular cloud. The gaseous component can be traced using for instance the $J = 1 \rightarrow 0$ transition of the ^{12}CO molecule. A study by Blitz (1981) showed that most remnants of molecular clouds associated with OB associations are situated at the edge of the stellar aggregate. Furthermore, we can determine the gas-to-dust ratio. In Sco OB2 the only remnants of the parent molecular cloud are the clouds forming the Ophiuchus Complex of Molecular Clouds. CO observations of this region were made by one of us (EDG) using the Columbia 1.2-m telescope on Cerro Tololo. The instrument was built for large-scale surveys of the Galactic Plane, but is excellent for the study of large molecular clouds too. A preliminary investigation of the data shows that there is no clear 1-1 correlation between the gas and the dust (IRAS skyflux maps). This is probably due to the high UV flux in the associations.

A careful study of both the stellar content and the ambient interstellar medium can give us many clues to why and how the stars in the Sco OB2 association started to form about 15 million years ago.

We thank Dr. J.W. Pel for communicating the transformation formulae to derive the magnitudes in the Johnson system in advance of publication.

Table of Nuclear and Kinematic Ages

Association	t_{nuc} [10^6yr]	t_{kin} [10^6yr]
Sco OB2: Lower Centaurus Crux	10–13	
Sco OB2: Upper Centaurus Lupus	13–16	
Sco OB2: Upper Scorpius	3– 6	4.5

References

Bertiau, F.C., 1958. *AP. J.* **128,** 533.
Blaauw, A., 1946. "A Study of the Scorpio Centaurus Cluster" Thesis University of Groningen.
Blaauw, A., 1964. *Ann. Rev. of Astron. Astrophys.* **2,** 213.
Blaauw, A., 1978. In "Problems of Physics and Evolution of the Universe". Ed. Mirzoyan, L., Yerevan, USSR, p. 101.
Blitz, L. 1981. In "Giant Molecular Clouds in the Galaxy". Eds. Solomon, P.M., Edmunds, M.G., p. 1.
Collins, G.W., and Sonneborn, G.H., 1977. *Ap. J. Suppl.* **34,** 41.
De Zeeuw, P.T., and Brand, J., 1985. In "Birth and Evolution of Massive Stars and Stellar Groups". Eds. Boland, W., van Woerden, H., p. 95.
Doom, C., de Greve, J.P., and de Loore, C., 1985. *Ap. J.* **290,** 185.
Elmegreen, B.G., and Lada, C.J., 1977. *Ap. J.* **214,** 725.
Lub, J., 1979. *The Messenger* No. **19,** p. 1.
Maeder, A., 1981. *Astron. Astrophys.* **93,** 136; **99,** 97; **102,** 401.

Visiting Astronomers (April 1 – October 1, 1986)

Observing time has now been allocated for period 37 (April 1 – October 1, 1986). As usual, the demand for telescope time was 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: Keel/de Grijp/Miley, Zuiderwijk/Shanks, Fusi Pecci/Buonanno/Corsi/Renzini/King, Chincarini/Carpino, Bässgen/Grewing/Krämer/Maluck, Ulrich/Perryman, Festou/Dennefeld, Grec/Gelly, Mathys/Stenflo, Holweger/Steenbock/Steffen.

May: Holweger/Steenbock/Steffen, Schmutz/Hamann/Hunger/Wessolowski, Nissen/Gehren/Kudritzki, Magain, Schoembs/Pedersen/Marschhäuser, Kunth/Arnault/Tarrab, Epchtein/Nguyen-Q-Rieu/Winnberg/Lindquist/Le Bertre, Encrenaz/Lecacheux/Combes, de Muizon/d'Hendecourt, Chelli/Carrasco/Cruz, Zinnecker/Chelli/Perrier.

June: Danziger/Binette/Matteucci, Jarvis,