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SUMMARY OF IAU COLLOQUIUM 191: THE ENVIRONMENT AND EVOLUTION OF BINARY AND MULTIPLE STARS

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RESUMEN

Se presenta un resumen del Coloquio 191 de la UAI "El Entorno y la Evolución de las Estrellas Binari Múltiples". Esta conferencia se celebró en Mérida, México, en febrero de 2003, y estuvo dedicada al Dr. Arc Poveda, por sus importantes contribuciones al campo de las estrellas binarias y múltiples y su dinámica. conferencia se organizó para discutir los principales desarrollos que están ocurriendo en los campos de forma de binarias y múltiples, su evolución, su dinámica y el entorno en donde se forman y evolucionan.

ABSTRACT

A summary is given of the IAU Colloquium No 191 "The Environment and Evolution of Binary and Mul Stars." This conference was held in Mérida, Mexico during February 2003 and dedicated to Dr. Arcadio Po for his major contributions to binary- and multiple-star systems and dynamics. The conference was organ to discuss the major developments that are occurring in the fields of binary- and multiple-star format evolution, dynamics, and the environments where they form and evolve.

Key Words: **BINARIES: GENERAL — GALAXY: OPEN CLUSTERS AND ASSOCIATIONS STARS: FORMATION — STARS: EVOLUTION — TECHNIQUES: HIGH ANGUL RESOLUTION**

1. INTRODUCTION

This was a very successful and interesting meeting, held in the beautiful city of Mérida, Mexico, capital city of the Yucatan State. The meeting was organized by Colin Scarfe and Christine Allen and held in honor of Dr. Arcadio Poveda who was born in Mérida. It is fitting that this conference was held in the heart of Maya land and near famous Mayan archeological sites, such as Uxmal and Chichén Itzá, because the Maya are known for their careful astronomical observations and the famous (and accurate) Mayan calendars. Also, because the conference includes n-body interactions and collisions, it is fitting that the conference is located near the Chicxulub impact site which is associated with the K-T extinction some 65 Myr ago.

About 80 people attended the colloquium from over 20 different countries. The primary aims of

both close and wide binaries and multiple star tems. It is noteworthy that much of the progres these fields arises from vastly improved parallaxe a large number of stars, made primarily from parcos. Also important are high precision radia locities (e.g., from CORAVEL and others), opt infrared and radio interferometry, as well as di high resolution images from ground-based adap optics (AO) telescopes and from the Hubble S Telescope. On the theoretical side, more powe high speed computers, as well as more realistic phisticated modeling and simulations of binary multiple star interactions, have led to new insi into the formation, dynamical evolution and stab of binary and multiple star systems. This mode in fact, explains much (but not all) of what is observed in terms of the distribution and frequen of binary as well as hierarchical star systems in field and in star clusters.

2. OBSERVATIONAL PROPERTIES AND STATISTICS OF BINARY STARS IN TH FIELD

Several papers were presented about the st tical properties of binary and multiple star syst

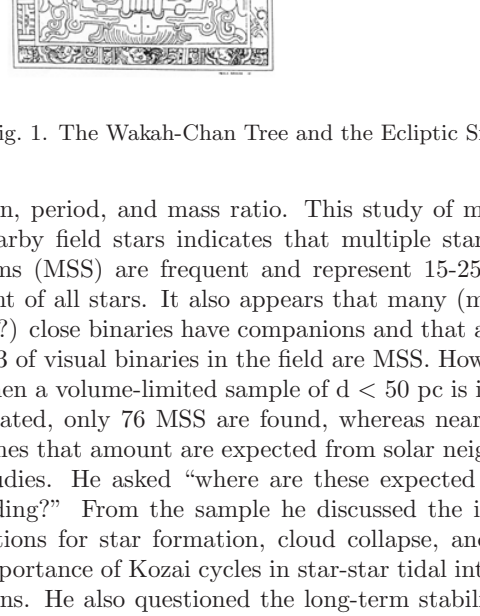

Fig. 1. The Wakah-Chan Tree and the Ecliptic Snake

tion, period, and mass ratio. This study of mainly nearby field stars indicates that multiple star systems (MSS) are frequent and represent 15-25 percent of all stars. It also appears that many (maybe all?) close binaries have companions and that about 1/3 of visual binaries in the field are MSS. However, when a volume-limited sample of d < 50 pc is investigated, only 76 MSS are found, whereas nearly 10 times that amount are expected from solar neighbor studies. He asked "where are these expected MSS hiding?" From the sample he discussed the implications for star formation, cloud collapse, and the importance of Kozai cycles in star-star tidal interactions. He also questioned the long-term stability of many triple systems and pointed out some unusual multiple systems that defy explanation under current ideas of formation and evolution. In another interesting statistical study, Netzach Farbiash and Raphael Steinitz reported on the investigation of correlations between rotational spin velocities in a sample of over 1000 binary systems. They found significant correlations between the projected spins of the components of binaries. Checks against artificial binaries indicate that the observed correlations are real and that their results indicate that the spin axes of the binary components are preferentially parallel and oriented perpendicular to their orbital planes. This result is relevant to the various theories of formation and evolution of binary stars discussed at this conference. Further work is planned to determine the

Their study was based on CORAVEL radial ve
ities of field and open-cluster solar-type stars.
use of Hipparcos parallax data permitted an u
ased sample of stars to be studied. They dete
nearly 90 spectroscopic binaries in the sample
P < 10 yrs. About 14 percent of the stars in
tigated are spectroscopic binaries (SBs); no sig
icant difference in stellar properties was found
tween field stars and cluster members. This st
indicated a bi-modal distribution in properties
broad period peaks near ∼20 days and 750 da
which perhaps suggests two different processes
generate close (P < 10 yrs) binary systems.
related paper, Anne Eggenberger (with Halbwa
Udry and Mayor) discussed the extension of the
inal Duquennoy & Mayor (1991) CORAVEL st
by adding additional K-stars with Hipparcos pa
laxes to the sample and extending the time bas
over a decade. They presented initial results on
statistical properties of an unbiased sample of F
stars. This work focused on the long period
tems. Their results indicated that binary stars
the dominant mode of star formation - that is "n
stars are found in binary and multiple systems
not." They also found that twins (stars of e
mass) are common in the shorter-period binarie

Hans Zinnecker, with co-authors Köhler
Jahreiss, presented the results of a study of visua
naries and multiple stars among Population II s
The stars were selected from their proper mot
and nearly 200 stars were investigated for dupl
and multiplicity using infrared interferometry, ad
tive optics and wide field imaging. They found
binaries and 6 triples among this sample. This
dicates a binary frequency of 15-25 % which is s
lar to field stars but much lower than the freque
found in young clusters. As discussed in their pa
the study of old (halo/metal-poor binaries) is im
tant because these systems were formed under
different conditions than were younger disk star

Helmut Abt and Daryl Willmarth presented
results of their ongoing radial-velocity investiga
of nearly 300 F7-K7 stars. This study is being
ried out primarily to search for very low-mass c
panions and to determine if there is a "brown-d
desert" among binary members. With an ave
precision of 100 m/s, their study can discover se
daries with masses down to about $0.01M_{\odot}$. The
servations made so far indicate that over 20 per

double and multiple star systems were reviewed and evaluated by Arcadio Poveda and Christine Allen. They found that the distributions of the semi-major axes of these systems carry important information about the conditions and mechanisms of formation, as well as the dynamical evolution of the orbital properties of the stars over time as they encounter molecular clouds, spiral arms, massive stars etc. An important aspect of this research is the dissolution times of the wider systems. For the purpose of the study, the systems were segregated into different age groups (primarily based on space motions and metallicities), and orbital properties (i.e. separation) from various catalogs. In this paper, Poveda and Allen tried to make sense out of dissolution times of binary systems, frequency distributions of major axes, runaway stars, and binary star formation and destruction processes. One of the more interesting results of their study is that the distributions of the orbital separations of all age groups (from very young to old disk stars) seem to follow the classic 1925 Öpik distribution law – i.e.:

$$f(s)\ ds \sim ds/s$$

in which "s" is the observed separation between components (see Öpik 1925; 1929). They also explained most runaway stars as resulting, not so much by ejections from binaries in which one component undergoes a supernova explosion, but more likely from ejections from close encounters that occur in more dense (possibly contracting) star forming regions. I am sure that Dr. Öpik would be happy that his distribution law apparently still holds true today even though why it does so is not fully explained.

In a related paper on binary star separations, Michael Sterzik addressed the vexing question "Are binary star separations related to their systemic masses?" He presented the results of various studies of field binaries with very low mass (dM8+ stars), low mass (dM2-dM5 stars) and binaries with solar mass primaries. Dynamical decay models predict an increase in multiplicity with increasing systemic mass chiefly because the more massive systems are more tightly bound and can survive longer. The frequency of field solar-type binaries is ∼57 ± 10 %, while low-mass (dM-type) binaries have a frequency of 31-42 % (depending on the particular study). However, very low-mass systems are much less common with a frequency of 10-15 %. Sterzik concluded

in binary and multiple star research. Instrum
like CHARA and the Navy Prototype Optical
terferometer (NPOI), along with others, are be
ning to produce some very interesting results.
example of this potential was shown in the repor
Christian Hummel of observations of the hierarch
triple system η Vir with NPOI. In this study a
the components of this triple system were reso
and their relative positions were measured over
with a precision of ± 0.07 mas. From the astro
ric and spectroscopic data, the orbital and ph
cal properties of the stars were determined for
first time, with some interesting astrophysical im
cations.

High-precision red spectroscopic observat
carried out recently by Frank Fekel revealed an
creased multiplicity in three well studied binary
triple systems, V815 Her (an SB1 binary), and
140122 and 77 Cyg (both known triple syste
Frank related a fascinating saga of luck, perse
ance, a "midnight mistake" and the "unexpe
expected results" in unraveling the secrets of t
three star systems.

3. NOMENCLATURE OF MULTIPLE STA SYSTEMS

In a special ses
at IAU Colloquium
William Hartkopf
Brian Mason discu
the current status
an effort to ado
the growing confu
in double and m
ple star nomencla
brought about by m
advances in techno
and reduction meth
New techniques
include interferom
(both long-baseline
speckle), adaptive op
(AO), and high-preci
spectroscopy have led to a rapid proliferation in
number of stars with identified companions. A
the discovery of increasing numbers of new ob
classes - such as extra-solar planets and br
dwarfs as companions to single and double s
adds to this problem. For example, interferom
and AO techniques now permit measurement of

astrometric and interferometric space missions such as the Space Interferometry Mission (SIM) and GAIA, as well as missions to search for extra-solar planets, such as COROT and Kepler, should lead to the discovery of hundreds to thousands of complicated multiple star/planet systems. The progress made on the adoption of a long-lasting, versatile nomenclature and designation scheme was discussed, and examples were presented in the context of the Washington Multiplicity Catalog (WMC). Every effort is being made toward getting this nomenclature system right, since, as Christian Hummel commented, "The future is longer than the past." A thorough discussion of this important topic, as well as additional information about the WMC, can be found at the WMC website: ad.usno.navy.mil/wds/newwds.html.

At the conference, an amazing discovery was found for a possible Maya Multiplicity Star Codex. An example of the Maya system is given below for the multiple star system χ^1 UMa.

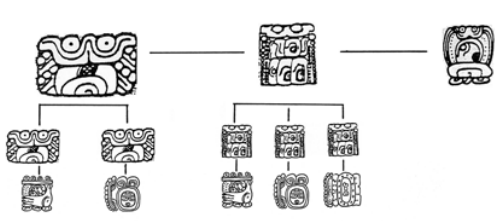

Fig. 2. Mayan Multiple Star Classification System as applied to χ^1 UMa.

4. OBSERVATIONAL RESULTS FOR VERY YOUNG BINARIES

In a paper on multiplicity and outflow activity of newborn stars, Bo Reipurth discussed the strong observational evidence for multiplicity among the very youngest low mass stars. High-resolution images of a large number of Herbig-Haro (HH) objects display manifestations of significant outflows that include complicated bow shocks and jets. Spectacular images of several HH objects also show knots in the outflows and wiggles in the jets. As discussed by Reipurth, the HH flows represent fossil records of the birth of binary systems. Some of the observed periodic variations shown in the images are believed

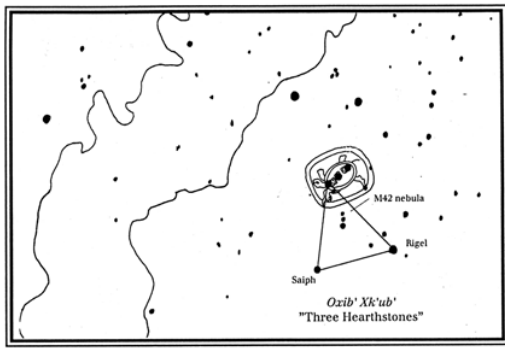

Fig. 3. Maya star map of the Orion region. The M constellation "Three Hearthstones" is shown. The M depicted Orion's belt as a turtle. The Orion Ne (M42) and Trapezium cluster are shown.

evolution of the young binary system is occu and that the orbits are often unstable and decay time scales of $\leq 10^5$ years. Studies of HH object dicate that most (∼80 percent - if not all) giant objects are binary or triple systems. Understa ing the formation and evolution of these objec important because, as Bo Reipurth said, "If w not understand how stars form, we cannot know galaxies form."

In the paper, "Orbital Motions in Binary tostellar Systems," Luis Felipe Rodriguez discu high spatial resolution (∼100 mas) Very Large ray (VLA) observations of several low-mass (2 $M_\odot$) young-stellar-object (YSO) proto-binary systems in the Taurus and ρ Ophiuchi star-forn regions. The large luminosities observed for t YSOs support the idea that young protostars de most of their luminosity from accretion processes not from nuclear reactions. The rewards of carr out systematic long-term observations were cle demonstrated in this paper. By combining V observations carried out for nearly 20 years, l term orbital motions have been detected for som the targets. For example, in the case of the fam YSO prototype, T Tauri, VLA observations o southern component, T Tau-S, reveal what app to be orbital motion (defined by a partial astron ric ellipse) between 1983 and 1998. However, servations made after 1998 do not appear to fit preliminary astrometric orbit and indicate that star is not following the expected orbital beha

this suggestion - see Hummel et al. (2004 - in press). The planned additional observations should clarify this interesting situation. Rodriguez and collaborators plan more radio observations with the VLA and Very Long Baseline Interferometer (VLBI). In the next several years, improved high spatial resolution observations of YSOs with the Expanded Very Large Array (EVLA), Atacama Large Millimeter Array (ALMA), and the Square Kilometer Array (SKA) should produce some very exciting results and provide important constraints on the early phases of stellar evolution.

Guillem Anglada presented a paper on VLA observations of disks and jets of selected young close binaries. High angular resolution observations now available at radio wavelengths make it possible to resolve the binary components and in some cases detect small orbital motions. Observations of SVS-13, NGC 1333-VLA2, and L723-VLA2 indicate that these radio sources are very young, close (25-75 AU separation) binary systems. Moreover, there is strong evidence that NGC 1333-VLA2 is a young multiple star system with a separation of ∼25 AU in which one component dominates the flux at 3.6 cm while the other component dominates at 7 cm. These results suggest that the development of disks and jets can proceed in different ways for each component a binary system. Observations of higher angular resolution, and the improved signal-to-noise expected in the near future, of these and additional young radio sources, will be important to help understand the formation and properties of the disks and jets in very young star systems.

No meeting on binary stars would be complete without a paper about the "Mother of all binaries," η Carinae. This star came to the attention of southern observers when it first dramatically brightened (known as the "Great" eruption) during the 1840s. Since that time, η Car has been extensively studied and has been identified as (one of) the most massive binary stars in our galaxy. Yousaf Butt reported on X-ray observations of η Car made with ROSAT, ASCA, RXTE, Beppo-SAX, and CHANDRA as well as coordinated near-IR and radio observations. Spectroscopic and X-ray observations secured over the last decade reveal the presence of a period of P = 5.52 years. The variations in the observed X-ray emissions are believed to arise from collisions of the binary star components with strong

to observe η Car during June 2003, when th
ray dimming is expected to occur during the p
tive periastron passage. They include coordin
high energy observations (γ-ray) made with IN
GRAL and X-ray observations made with CH
DRA. These observations should provide an im
tant test of the still-disputed binary hypothes
η Car. This popular binary model predicts an
hancement in the γ-ray flux shortly after perias
passage near the time of the X-ray "eclipse." Co
tation with IAU Circulars indicates that the X
eclipse occurred as expected during June 2003
IAU 8137/38). The results from INTEGRAL
yet to be reported at the time of writing.

5. OBSERVATIONAL RESULTS FOR BINA STARS IN CLUSTERS

Fig. 4: Searching for companions to binary star systems.

Binary stars
clusters can be r
ily discovered
investigated using h
precision radial-velo
measures. With mo
instrumentation
using cross-correla
techniques, radial
locities of better tha
km/s accuracy can now be obtained for solar
stars in nearby (d < 300 pc) clusters. Morec
the availability of multi-object fiber feeds per
simultaneous observations of up to hundreds of s
each night. This has lead to the identificatio
nearly all spectroscopic binaries with periods
than about several years in nearby open clus
Several papers were presented that focus on
observations of binaries in clusters while two pa
dealt with the relatively new field of binarie
nearby galaxies.

In the paper "Binaries in Open Clusters: Orb
Parameters and Stellar Astrophysics," Bob Mat
discussed the results of his detailed study of the s
age ($\tau \sim 4.5$ Gyr) open cluster M67. Many bi
and multiple star systems have been detected in
rich cluster. The frequency of spectroscopic bina
in M67 is 19 ± 4 %. This value is comparabl
field spectroscopic binaries but is probably also
underestimate of the number of binary system
M67 because the long period binaries are under
resented. Precise photometry of the cluster indic

binaries in M67 is quite high, leading Mathieu to remark that "M67 should not be considered a cluster of stars but a cluster of binaries." In his "Day at the Zoo," Mathieu briefly discussed the properties of interesting and rare binaries in M67. These include numerous blue stragglers (seven of these are SBs with known orbits), an eclipsing binary (S986) located at the cluster turn-off, several coronal X-ray binaries (four W UMa systems) and some stars that may have evolved through the common-envelope stage of binary-star evolution. He discussed the presence of several unusual binaries in terms of binary-evolution theory (binary mass-transfer and loss) and the possible effects of collisions and encounters with other cluster members.

Rainer Köhler and an international team of investigators tried to answer the "age-old question" of what causes the low binary frequency in the Orion Nebula Cluster (ONC)? Using AO techniques, they studied the multiplicity of about 220 stars in the outskirts of the young ONC. The stars selected for study are located about 0.7 to 2 pc from the cluster center - the Trapezium Cluster. From previous (less sensitive) studies the effectively zero-age ONC has been found to be populated by a much lower number of binaries and multiple stars than young star forming T-associations. The major aim of this study was to search for the cause(s) of the apparent frequencies of solar and low mass binary and multiple star systems in this and other young clusters. The outer regions of the ONC were selected for study because these regions have fewer stars, and binaries and multiple star systems are less likely to be disrupted from tidal (dynamical) interactions. The results of this interesting study show that the multiplicity fraction of low(solar)-mass stars is low (about 5-8 %), and does not depend on the distance from the cluster core. However, the frequency of high mass multiple (OB) stars is higher in the inner regions of the ONC (about 30 %). The frequency appears to decrease from the center to the outskirts of the cluster.

Several more related papers were presented. Gene Milone presented the initial results of an analysis of the photometric light curves for the eclipsing and ellipsoidal binaries discovered in the globular cluster 47 Tuc with the Hubble Space Telescope by Ronald Gilliland and collaborators. So far these faint cluster binaries do not have radial-velocity curves, which severely limits what can be determined. He

ical isochrones from stellar-evolution codes. Bec
the age, distance, [Fe/H], colors, and reddening c
Tuc members are well known, it is possible to use
Mass-Luminosity relation and color-T_{eff} relation
estimating the physical and orbital parameters o
stars. This method shows great promise and sh
also be useful in determining the physical pro
ties of the thousands of eclipsing systems discov
over the last decade in the Magellanic Clouds
M31 from microlensing programs such as MAC
and OGLE.

In a related paper Christine Allen discussed
presence of young stars found far from the gala
plane. Two of the best studied cases of "runa
stars" are AE Aur and μ Col. As suggested dec
ago by Allen and Poveda, the best explanation
finding these young stars where they do not be
is from interactions in the core of young clusters
subsequent ejections. In the same session Lex K
discussed the importance of high-mass x-ray b
ries to the understanding of massive star forma
and evolution. He reported on coordinated x-ray
Hipparcos observations. He discussed the "D
Compromise" in which it appears likely that no
type II supernovae result in neutron stars while b
holes result from more massive γ-ray bursters.

Mattias Eriksson and Hans Veenhuizen repo
on the investigation of Fe II fluorescence by ph
excitation from accidental resonance (PAR) in al
30 symbiotic variable stars observed in the UV
IUE. PAR-mechanism-pumped Fe II line emis
channels were discovered in 8 systems, including
well studied systems RR Tel, AG Peg, V1016 C
and AG Dra. They discussed the information
can be gained about plasma physics and dyna
from the study of the PAR Fe II fluorescent
in symbiotic stars with different orbital and st
properties.

A short report on the initial results from coo
nated photometry of the well known cataclysmi
nary IR Gem was presented by Kam-Ching Leun
behalf of an international team lead by Li Zong
The observations took advantage of the longitud
separation of 160°between Nanjing and Nebrask
study various periodicities apparent in the light
ations. The photometry of this 98.5-min. bi
showed complicated behavior during quiescence

6. ECLIPSING BINARIES IN THE GALACTIC BULGE AND NEARBY GALAXIES

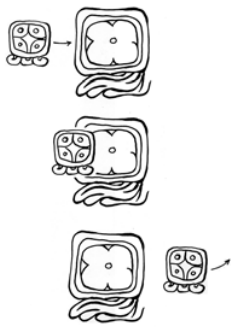

Fig. 5: Maya representation of an eclipsing binary star.

Carla Maceroni discussed the development over the last decade of large photometric data bases on variable and eclipsing binary stars that have resulted from several microlensing surveys of the galactic bulge and the Magellanic Clouds. For example, the EROS, OGLE and MACHO programs have discovered over ten thousand new eclipsing stars so far, and hundreds of thousands of additional eclipsing (and pulsating "single-star") variables are expected to be discovered in the near future from space missions such as the COROT, Eddington, Kepler, and GAIA missions. In her paper she discussed mining these data sets to understand the formation and evolution of close binaries - in particular for identifying the "missing links" of binary stellar evolution. She stressed the need to carry out the analysis of the light curves of large numbers of stars in an automatic way.

Glenn Bayne discussed photometry of eclipsing binaries in the Small and Large Magellanic Clouds being carried out as part of the microlensing observations in astrophysics program at Mount John University Observatory, New Zealand. Light curves for over one hundred eclipsing binaries have been obtained so far. In this talk he discussed the determination of photometric and orbital properties for two interesting systems. In a related paper, Guinan, Ribas, and Fitzpatrick discussed the progress of an ongoing HST and ground-based program of observing eclipsing binaries in the Local Group galaxies. This study is being made to determine accurate distances and the physical properties of the stars as well as probing the structure and evolution of their host galaxies. The analysis of the light and double-line radial-velocity curves yields stellar masses and radii; while the temperatures and interstellar extinction are measured from the HST 115-850 nm spectrophotometry. Independent measures of three eclipsing binaries located in the LMC bar region yield a distance of d = (Guinan 2004).

7. THEORETICAL APPROACHES TO MULTIPLE SYSTEMS AND THEIR FORMATION

Fig. 6: Maya glyph indicating "captured" star. This could be relevant to several papers at the conference that focus on stellar mergers.

Mauri Valtonen
cussed methods and
lutions of the clas
three-body problem.
pointed out that
solution of the th
body problem is im
tant because three b
processes play impor
roles in the dynamic
lution of many star
ters. Because mo
ing the exact 11-D s
tion of three-body or
"could require comp
runs near the age of the universe," he discussed
lutions from 3-body perturbation theory and 3-b
numerical methods. The solutions turn out to
either statistical or deterministic in nature, dep
ing on the initial conditions. He applied these
culations to the observed properties of binary
multiple systems with some very interesting res

In a related paper, Rosemary Mardling repo
on a new formalism for studying three-body i
actions. This new formalism permits the dete
nation of the short-term and long-term stabilit
any triple-body configuration, along with dete
nations of energy and angular-momentum tran
during scattering and capture-process events.
procedure also gives the prediction for the final
come of an unstable triple system and the stud
resonance-capture processes. Some of the result
the effects of a third body on the orbits of close p
were nicely illustrated with superb animations.
example, if the orbital eccentricity is large, the
tiary body can gain sufficient angular energy t
summarily ejected. In some cases this could exp
"runaway stars." Interesting analogies in this tr
ment have been made to quantum mechanics.
some cases resonances can develop and the orbi
the third body and closer binary "talk to each oth
Also, new criteria for the stability of three and
body orbits have resulted from this work.

In another paper on the restricted three b

hole components. Examples of orbital interactions with different third-body masses and external forces were explored and the results discussed. He found that both the equilibrium points and solution curves can become quite different from those of the classical isolated three-body problem.

Before taking a hiking trip to traverse the high Andes, Sverre Aarseth presented a paper on the formation and evolution of hierarchical star systems. In that paper he gave an expert guided tour of the "hierarchical stellar zoo." His calculations (using realistic N-body simulations appropriate for more dense star forming regions) show that most compact triple systems are formed from binary-binary collisions. Triple systems tend to build up over time scales of 2-3 Gyr. Also, he finds that many stable (long-lived) quadruples and higher-order multiples can be expected. The higher orders of multiplicity can have various and diverse origins. Over time, external interactions can also cause an increase in the orbital eccentricity that can lead to instability of the system. Under some conditions, systems can be disrupted by a slingshot mechanism. Sometimes these reactions are sufficiently energetic to eject the stars with high velocity, thus resulting in "runaway stars." He discussed the expected properties of hierarchical systems such as quadruples, quintuples and sextuples. He made an interesting analogy between binary (and higher-order) systems, and molecules.

Tomoyuki Hanawa presented the results of 2-D numerical simulations of the accretion of gas from circumbinary disks to the primary and secondary stars of proto-binary systems. The somewhat surprising result of this study is that the primary (the more massive component) accretes more than its lower-mass companion. This seems to occur under various initial binary-system characteristics, and with different accretion conditions and orientations. In these simulations the accretion occurs onto the primary either through the L2 and L1 points, or through the L3 again (with the same result) onto the primary star. According to these simulations, the primary star's mass increases so that the mass ratio M_s/M_p decreases with time. These simulations appear to be consistent with recent observations that the primaries in young binary systems have more massive accretion disks than the secondary stars.

Masahiro Machida discussed the application of three-dimensional MHD nested-grid simulations to

perturbations, the rotation speed, and strengt
the magnetic field. The end result is the collaps
the gas and the formation of an opaque core.
pending on initial conditions, the resulting cores
have a wide variety of shapes that include bars, ri
disks and small spheres. Binary and multiple
systems can form from the bar, disk and ring m
els, while single stars form from the small sph
These simulations could be scaled to study the
mation and evolution of galaxies.

8. ASTROPHYSICAL PROCESSES OF MULTIPLE STARS IN CLUSTERS

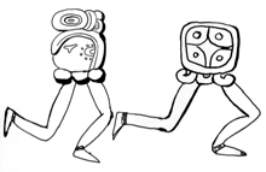

Fig. 7: Mayan glyphs representing runaway stars!

Matthew Bate
cussed the results of
3-D calculations.
studied the effects
star formation and
lution in dense star
ters have on the pro
ties of binary and m
ple stars. He emplo
a state of the art "
Generation" 3-D Hydrodynamics code that yie
the first fully resolved calculations of fragmenta
as small as ∼1AU. He ran the simulations by v
ing the initial conditions of the cluster (chan
mainly the initial density). The effects of accret
interactions with circumbinary and circum-mult
system disks, dynamical interactions, and the
tial density of the stars within the star-forming
gion were all studied. Fascinating animations of
fragmentation, accretion, and capture processes
ing place over a 200,000 year time-scale were
sented. About 70 percent of the stars in the clu
are expected to be binary and multiple star syst
(in good agreement with observations for young
clusters). An interesting result of these studi
that the simulations initially produce nearly e
numbers of stars and brown dwarfs, but that
brown dwarfs result primarily from "arrested de
opment", being ejected from the cluster before
can accrete enough matter to become stars. C
and wide binaries are formed as well as a va
of wide multiple-star systems. These simulation
not predict brown dwarfs as members of close s
mass pairs.

In a related study Cathie Clarke discussed
results of simulations of the formation (and dis

interactions and also the augmentation of the star masses from competitive accretion. As in the results of Bate, low-mass objects (like low-mass dM stars and brown dwarfs) appear to exist as a result of their early ejection, before they acquire sufficient gas to become stars. Thus only a few brown dwarfs are expected to be found in the cluster as single stars or members of close binary systems. Also, the modeling predicts that a significant number of brown dwarfs (and low mass late dM stars) could be hierarchical outliers of binary systems. It also has been found that binaries originating in the denser parts of the star-forming region (molecular cloud) have a higher gas supply and get a head start over the other stars. This advantage may result in higher-mass systems.

Christine Allen, with Poveda and Hernández-Alcántara, revisited their old, young friend the Trapezium cluster. The chief aim of the new study was to examine the stability of a number of wide binary and multiple star systems in this very young cluster. In an earlier study, Allen and Poveda had found evidence that some wide multiple stars in this cluster are dynamically unstable. These systems should evolve by ejecting one or more components either into hyperbolic trajectories, or into loosely bound wide orbits. In the latter case these rapidly evolving systems are transformed into hierarchical configurations. This study was based on astrometry of the binary and multiple star systems dating back to 1830. By carefully combining the older (less precise) data sets with more recent, more accurate, measures from the WDS Catalog of Observations, the authors found that most of the systems studied did not show significant motions. However, a few systems (e.g. ADS 2843 and ADS 13374) show large transverse motions that might indicate that they are escaping from the cluster. Overall, this study now uses about 170 years of observations and it lends support to the concept that the Trapezium binary and multiple stars are essentially unstable systems with lifetimes of a few million years. This work also confirmed the previous result of Allen and Poveda that there is no observational evidence for systematic expansion, or contraction, of the orbits of any of the systems. This study is an excellent illustration of the importance of historic data sets.

9. VERY LOW MASS COMPANIONS (RED DWARFS & BROWN DWARFS AND PLANETARY COMPANIONS)

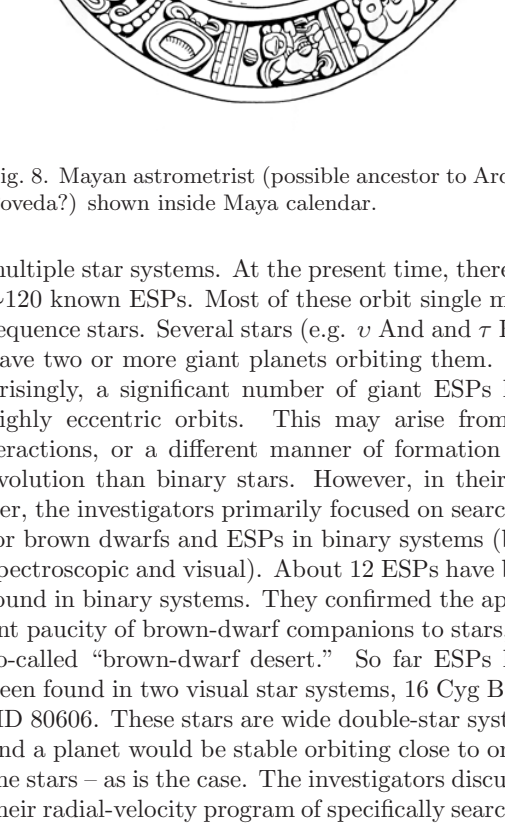

Fig. 8. Mayan astrometrist (possible ancestor to Arc
Poveda?) shown inside Maya calendar.

multiple star systems. At the present time, there
∼120 known ESPs. Most of these orbit single m
sequence stars. Several stars (e.g. υ And and τ I
have two or more giant planets orbiting them.
prisingly, a significant number of giant ESPs
highly eccentric orbits. This may arise from
teractions, or a different manner of formation
evolution than binary stars. However, in their
per, the investigators primarily focused on searc
for brown dwarfs and ESPs in binary systems (
spectroscopic and visual). About 12 ESPs have
found in binary systems. They confirmed the ap
ent paucity of brown-dwarf companions to stars
so-called "brown-dwarf desert." So far ESPs
been found in two visual star systems, 16 Cyg B
HD 80606. These stars are wide double-star syst
and a planet would be stable orbiting close to o
the stars – as is the case. The investigators discu
their radial-velocity program of specifically searc
for short period planets (and brown dwarfs) in si
line spectroscopic binaries (SB1s). They repo
that none have been detected so far. Care mus
taken in measuring the radial velocities of SB1
tems because many with cool-star components
expected to be magnetically active, having stars
and plages. These possible surface inhomogene
could corrupt the measured RVs, leading possibl

cent discovery of a dust ring around the young active early K2 V star, ϵ Eridani. This disk or ring could be a young analog to a Kuiper-belt structure. In our solar system dozens of Kuiper-belt objects, mostly orbiting outside the orbit of Pluto, have been found so far. Jiang's investigation focused on the long-term stability of belts of that kind around stars with known planets. The results indicate that most extra-solar planetary systems can have Kuiper-belt-like populations at their outer regions. However, they report that Kuiper-belt structures are unstable in the presence of a massive planet with a highly eccentric orbit (e $<$ 0.8). The belt width also appears to increase with increasing values of the orbital eccentricities of massive planets in the system.

Rudolf Dvorak reviewed the status of observations and the theory of planets as members of binary star systems. So far, there is evidence of 7 planetary systems in binary stars - six are solitary planets and, in one system (55 Cancri), there are (at least) three planets. Planets can be stable in two configurations around binaries. In 'P'-type systems, a planetary orbit is stable far away from a close binary pair, while in 'S'-type systems, the planet orbits close to one of the stellar components of the wide binary pair (e.g. 16 Cyg AB). As an example, the author discussed the case of the γ Cep system, in which a planet has been found in an eccentric orbit (e = 0.21) at 2.1 AU from one of the stellar components of this SB2 binary (P = 70 years; a = 21 AU). The dependence of planetary-orbit stabilities on mass ratios, periods, inclinations, and separations was discussed, and interesting results were presented.

Thierry Forveille, in a paper presented by Stephane Udry, reported on the study of binary (and multiple star) characteristics of a volume-limited sample of about 100 low-mass dM stars. The characteristics of dM binary systems provide important diagnostics of star-formation processes, and the importance of gravitational interactions with other stars on these weakly bound low-mass systems over the age of the Galaxy. The multiplicity parameters (distribution of binaries, mass ratios, semi-major axes, eccentricities etc.) of this sample were determined and compared to a similar sample of solar-mass stars with some interesting results.

Ing-Guey Jiang discussed the formation of brown dwarfs. He discussed the current knowledge about the number and distributions of brown dwarfs in the

nary systems containing main-sequence stars) proposed that the majority of brown dwarfs m likely form through secondary fragmentation cesses. They are scattered, or removed, to large tances from the star-forming (gas-rich) region w they cannot grow into stars. Thus brown dwarf sult from a form of arrested development in w they are "thrown from their cradles early in life

10. NEW INSTRUMENTS, TECHNIQUES, A PROGRAMS

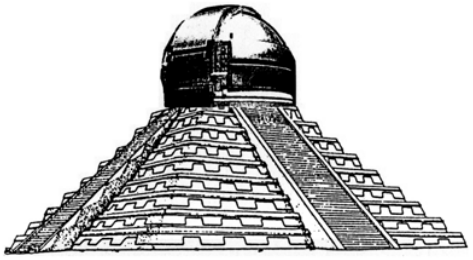

Fig. 9. Proposed observatory at Chichén Itzá.

Salvador Cuevas and his colleagues reporte an AO system being developed for the 2.1m S UNAM telescope being built in the Baja. This system is named "GUIELOA," which, in the Zap language, appropriately means "Our Eyes." The selected for the telescope has excellent average ing". The planned AO system covers the nea (I,J,H,K) and is expected to have very good ang resolution and fast read-out rates. Also, the sys will have coronagraphic capabilities for investiga stellar disks and jets. Some of the planned app tions of "GUIELOA" include the studies of bi and multiple star systems, as well as disks and of YSOs. The telescope and its instrumentation expected to be operational by 2005 and should duce many new interesting results.

At this conference the detection of low mass c panions (brown dwarfs and extra-solar planets) ing high-precision radial-velocity spectroscopy astrometry were discussed. Guinan, Ribas, and nou presented the results from an overlooked met of discovering low mass companions that uses light-travel-time effect (LTTE). A tertiary body biting an eclipsing binary produces periodic va

the LTTE depends primarily on the mass of the tertiary body relative to the eclipsing pair, the orbital period of the tertiary system (i.e. the semi-major axis), the orbital inclination, and the eccentricity of the third body. Scores of companions to eclipsing binaries have been discovered using the LTTE, while Guinan and collaborators have discovered a probable brown-dwarf (Mass $\simeq$ 0.04 $M_\odot$) companion to the Hyades eclipsing (dK + white dwarf) binary V471 Tauri. They reported on how high precision photometry and astrometry can be used as a method to detect low-mass stars and substellar objects in selected low-mass, uncomplicated, eclipsing binaries. In some cases the same method can also be applied to certain types of pulsating stars.

Andrea Richichi discussed long-baseline interferometry (LBI) and lunar-occultation (LO) methods for discovering and studying chiefly close binary systems. He discussed the statistical properties of the binary systems appearing in the CHARA Catalog (see Taylor et al. 2003) and those in the CDS. The LBI method is biased toward detecting binaries in which the magnitude difference of the components is < 3 mag. The LO method has greater dynamic range with Δm $\sim$4 mag being possible. The advantages and disadvantages of both methods were discussed. The LO method is simple and straightforward, inexpensive, fast (takes < 1 sec of observing time), yields angular separations of $\sim$1 mas, and can detect components whose magnitude differences are up to 5 mag. However, the LO method is 1-D only, serendipitous (fewer than 10% of stars are occulted by the Moon), and has a fixed time series. The LBI method can select the targets from over the entire sky, and repetitive observations and angular resolutions of < 1 mas are possible. However, the LBI method is expensive, requiring multi-telescopes and careful calibrations, the analysis is complicated, and the dynamic range is limited to < 3 mag. Also, the capabilities of ESO's Very Large Telescope Interferometer (VLTI - four $\times$ 8.2m telescopes, baselines = 130 m) were discussed. The VLTI was referred to as "a door to the future of interferometry," and that is certainly true! Very exciting results on binary and multiple star systems are expected. Angular diameter measurements of the component stars are possible in many cases.

The GAIA Mission is planned to carry out microarcsecond astrometry of most stars brighter than

date for GAIA is currently estimated for about 2
GAIA is expected to discover several million
eclipsing binaries and provide useful light and ra
velocity curves, as well as parallaxes for over 50
systems! In anticipation of this enormous and v
able data base, Tomaz Zwitter and Ulisse Mu
are studying a small sample of nearby eclipsing b
ries as a test bed for scripted automatic solution
light-curve and radial-velocity data sets. These
perimental datasets are similar to those expecte
be delivered by GAIA. Test solutions are being n
using a modified version of the Wilson-Devinney
gram. The initial results of this study are very
couraging.

11. CONCLUSIONS AND CLOSING REMAR

Fig. 10: Maya astronomer making last minute changes to his talk.

In addition to
oral papers previo
discussed here, t
were about tw
poster papers prese
at this colloqu
These poster pap
for the most part, c
plement the inv
and contributed
presentations, and
the other papers, c
a wide range of sub
matter. Unfortunately, there is no space to dis
them here. The poster papers include results f
photometric and spectroscopic studies of indivi
objects, as well as present the results of surv
and statistical and theoretical studies. They
cover a wide variety of objects from primordial s
to halo objects, as well as black holes. The re
should not overlook these many interesting pap

The oral and poster papers presented here cle
demonstrate the amazing progress made over the
decade in the fields of binary and multiple stars
the effects of, and/or on, the environments in w
these stars form and evolve. As discussed, new or
proved instruments and techniques, as well as sop
ticated modeling and improved theory, have bro
about a renaissance in this once-neglected field
colleague attending the colloquium, who is prima
known for his contributions to close binaries (mo
eclipsing binaries), confessed that, after atten
the colloquium, maybe he didn't choose the r

ing the next decade from new instruments and techniques, as well as advances in theory and modeling. During the next decade ground-based, radio, and optical facilities like ALMA, ELVA, SKA, and VLTI will be available. These, also with space-based missions such as Space Interferometry Mission (SIM), Spitzer Space Telescope (SST), James Webb Space Telescope (JWST), and later GAIA, along with others, should greatly expand our horizons and understanding of binary and multiple stars and will probably answer some questions raised here. However, they will most likely generate many new problems and questions.

Fig. 11. Two conference participants discussing the Trapezium Cluster during a coffee break.

It's difficult for me to remember exactly who was the originator of this idea about our understanding of close binary stars. It may have originated with Otto Struve (when confounded by the complexities of β Lyrae). However, I heard the same tale from F.B. Wood, Dan Popper and Mirek Plavec separately over the years. I paraphrase them: 'One of worst possible things that could befall researchers of interacting binary stars would to be taken (after death or by an UFO) to the astronomical objects of their attention (and often affection) and to be confronted by the star systems as they really are'. Now with new t
niques, such as long baseline interferometry and
rect imaging with AO techniques, or from space
large telescopes, it may not be long before we
actually "see" what we have previously inferred
modeled) from the observations. I look forwar
this day with some dread, but mostly with great
pectations to see and understand the beauty and
tricate complexities of the binary and multiple
systems.

I wish to thank Colin Scarfe and Christine A
for inviting me to participate in this colloquium
oring Arcadio Poveda. I have known Arcadio for
15 years and it is fitting that this meeting was
in his hometown of Mérida. Also, it is very fit
that it occurs at a time when so much progre
being made in the study of binary and multiple
systems, a field that Arcadio loves and helped sh
Thanks also is given to the local organizing com
tee, who did an outstanding job in organizing
meeting and providing many superb cultural ev
and visits. I also wish to thank Larry DeWarf at
lanova University for preparing the text and fig
for publication, as well as Scott Engle for helpin
proofread the manuscript before publication.

REFERENCES

Duquennoy, A. & Mayor, M. 1991, A&A, 248, 458
Guinan, E. F. 2004, New Astr. Rev., 48, 647
Öpik, E. 1925, AN, 223, 73
Öpik, E. 1929, AN, 235, 265
Taylor, S. F., Harvin, J. A., & McAlister, H. A. 2
PASP, 115, 609

Editors' note: As is also indicated in the Pre
the papers referred to in this summary by Yo
Butt, Thierry Forveille, Edward Guinan, Rosen
Mardling and Bob Mathieu are not included in
volume because no manuscripts were received by
editors. We can forgive Ed Guinan, however, in g
itude for his preparation of this summary.