Extremely Metal-poor Subdwarfs

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Introduction

The formation of our Galaxy and its evolution from an extended spherical halo to a highly flattened spiral disk can be convincingly documented by observing cool dwarf stars that have remained essentially unevolved since they formed billions of years ago. Model predictions of nucleosynthesis in stars, starting from a zerometal primordial composition, combined with a theoretical outline of the galactic collapse, have led to a coarse description of the history of our Galaxy, in which the oldest stars are extremely metal-poor and have highly eccentric galactic orbits with relatively small orbital angular momenta as compared with young disk stars.

Although the photometric and spectroscopic observations obtained in the last two decades have been found consistent with theoretical predictions, there still remain many open questions regarding the detailed kinematical and chemical evolution of the pre-disk stage of our Galaxy:

(a) What were the physical conditions in the interstellar gas out of which the stars formed during the galactic collapse phase? We know that the initially chaotic gas motions have settled towards a fairly regular rotation pattern, with a minimum dispersion in galactic orbital velocities.

(b) Was there a similar decay of random gas motions on a smaller scale, possibly related to the binary formation rate? Comparative observational evidence concerning the frequency of binaries among disk and halo stars rather seems to contradict such an assumption.

(c) How reliable are the current models describing the nucleosynthesis of heavy elements? Recently published abundance analyses of halo stars fail to confirm the even-odd effects predicted from purely explosive carbon, oxygen and silicon burning.

While it is certainly necessary to improve the methods used to interpret the available spectroscopic information, it seems indispensable to carry out new observations by taking advantage of fast modern detectors. Here, we present a preliminary report on the results of our programme which is designed to obtain radial velocities and element abundances of metal-poor subdwarfs. Since there are so few subdwarfs in the solar neighbourhood, we have aimed at reaching FG-type dwarfs fainter than $V \cong 8$, corresponding to distances $\gtrsim 50$ pc.

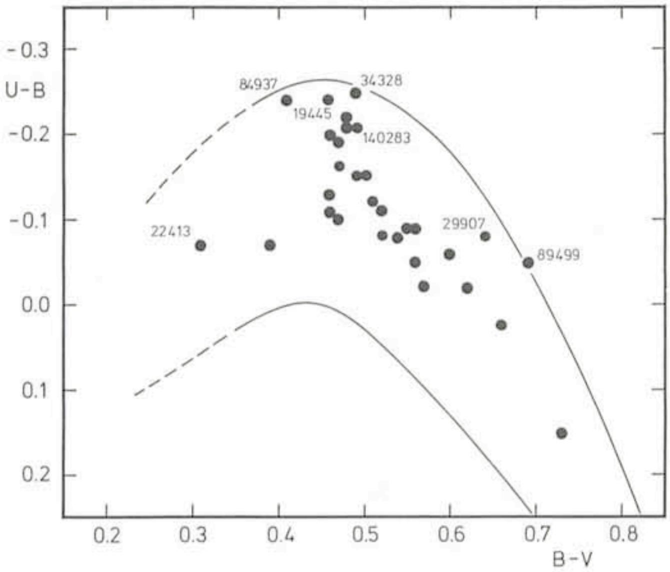

Fig. 1: *Two-colour diagram showing metal-poor subdwarfs observed at the ESO 1.5-m and MPIA 2.2-m telescopes. The lower curve is the Hyades main sequence. The upper curve represents the locus of stars with zero-metal content. Selected subdwarfs are labelled by their HD numbers.*

Observations

Due to the faintness of halo subdwarfs the limited observing time requires some kind of compromise concerning the selection of objects and spectral resolution. Accordingly, our observing programme was split in two parts: Low-resolution (40 Å/mm) spectra were obtained on IIIa-J emulsion with the B+C Cassegrain spectrograph at the ESO 1.5-m telescope. The stars on this list were selected according to their ultraviolet excess, δ (U-B) > 0.10, which was estimated to represent an upper limit of ~ ⅓ of the solar metal abundance. The low-resolution spectra were intended to measure radial velocities and to provide an improved estimate of the metal content. For the second part of the programme the apparently most metal-poor subdwarfs were observed with the echelle spectrograph and the Lallemand electronographic camera at the Coudé focus of the ESO 1.5-m telescope. The observations covered the blue spectral region from 3900 to 4400 Å, with a resolution of 150 mÅ, and the limiting magnitude for a 3-h exposure was $B \sim 10$. Additional spectra have been obtained directly with the f/3 camera at the Coudé focus of the MPIA 2.2-m telescope on the Calar Alto in Spain. These spectra are currently used to determine abundances of individual elements. All stars observed so far are presented in a two-colour diagram in Fig. 1, where the lower curve shows the Hyades main sequence, and the upper curve represents the positions of subdwarfs with zero-metal content. Some of the more interesting objects are labelled by their HD numbers.

The reduction of the echelle spectra is relatively simple, provided that a two-dimensional microphotometer and a computer with graphic interaction facilities are available.

It turns out that the quality of the reduced echelle spectra is comparable with that of conventional coudé spectra. No significant loss of resolution is encountered and, under favourable conditions, it is possible to measure line strengths down to ~ 10 mÅ.

Results

(1) Kinematic Properties of the Subdwarfs

All the low-resolution spectra were measured with the MPIA Grant comparator, and mean radial velocities were derived combining our results with radial velocity data found in the literature. Unfortunately, reliable trigonometric parallaxes are known only for a few stars, and most of the parallaxes at present have to be estimated from photometry. The resulting kinematic properties of our metal-poor dwarfs are displayed in Fig. 2, where orbital velocity components in the direction of galactic rotation, V′, are plotted as a function of metal abundance. This diagram is similar to the well-known h vs. δ(U-B) diagram of Eggen, Lynden-Bell and Sandage (1962, *Astrophys. J.* **136,** 748). It shows that only about half of the stars belong to the halo population. According to its colours, HD 22413 is possibly a blue straggler. However its parallax and orbital velocity are highly uncertain. Three of the halo sub-

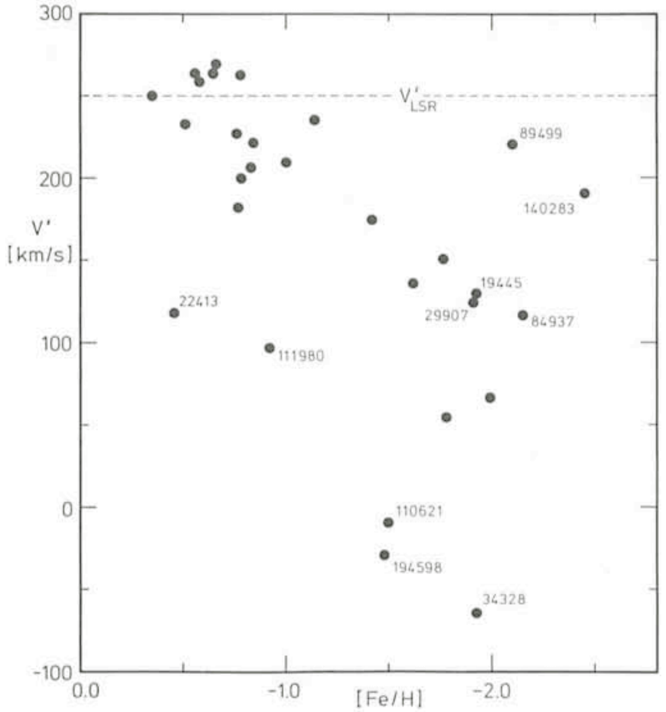

Fig. 2: *Galactic orbital velocities in the direction of galactic rotation for metal-poor subdwarfs as a function of [Fe/H], the logarithmic iron to hydrogen abundance ratio relative to the solar value.*

dwarfs, HD 34328, HD 110621 and HD 194598, move on retrograde galactic orbits.

HD 29907 turns out to have a total orbital velocity of ~ 400 km/s, which is near the local escape velocity of our Galaxy. Accordingly, this subdwarf belongs to the handful of kinematically extreme field stars (including BD+21°607, CD–29°2277, G238–30, G64–12, HD 134439/40, and possibly G21–33), which are known to impose important constraints on the modelling of our Galaxy. The adopted parallax for HD 29907 is a maximum value based on the position of the corresponding metal-poor main sequence.

Fig. 2 also illustrates that the rapid metal enrichment during the collapse phase of our Galaxy was accompanied by an increase in kinematic motions and a simultaneous decrease in the dispersion of orbital velocities and angular momenta. Tinsley and Larson (1978, *Astrophys. J.* **221,** 554) have proposed that the observed age dependence of the velocity dispersion of old stars was produced by a gradual decay with time of large-scale interstellar turbulent motions. If a similar decay with galactic evolution of small-scale turbulent motions took place, one might expect the frequency of binaries among halo stars to be *higher* than among disk stars, since the formation of binaries is supposed to depend on the state of local turbulence in the protostellar gas (Huang and Wade, 1966, *Astrophys. J.* **143,** 146). In fact, our observations appear to support this hypothesis. Comparison of our radial velocities with measurements of other authors reveals a scatter of radial velocity data shown in Fig. 3, where we have plotted the external probable error for a single plate, $\sigma(V_r)$. For stars like HD 89499, HD 29907, BD–3°2525 and HD 34328, radial velocity measurements differing by more than 20 km/s and up to 60 km/s indicate that these subdwarfs are probably spectroscopic binaries.

This result disagrees with empirical investigations of Abt and Levy (1969, *Astron. J.* **74,** 908) and Crampton and Hartwick (1972, *Astron. J.* **77,** 590), who found that at least short-period (spectroscopic) binaries seem to be *rare* among halo stars. On the other hand, a reinvestigation of the binary frequency among stars listed in the Nearby Star Catalogue reveals no deficiency of short-period binaries among high-velocity stars, provided that stars of sufficiently faint magnitudes (V > 7) are compared. In view of these contradictory results a more systematic approach to detect high-velocity spectroscopic binaries would be extremely valuable.

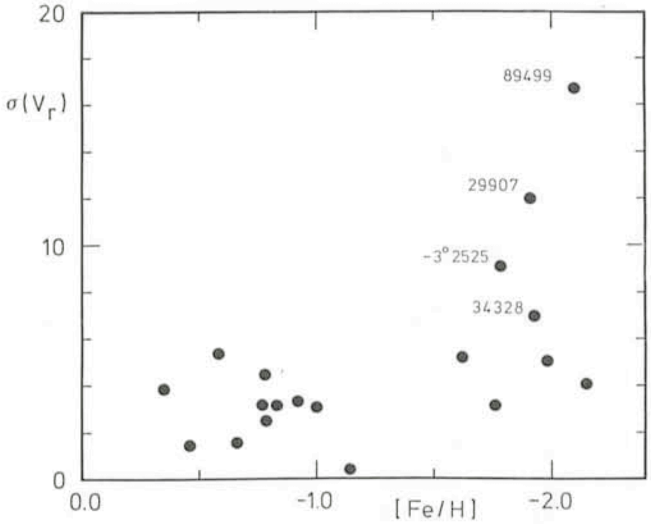

Fig. 3: *External probable error of radial velocities measured from a single plate as a function of metal abundance, including published radial velocities. Note the high fraction of possible spectroscopic binaries among the halo subdwarfs.*

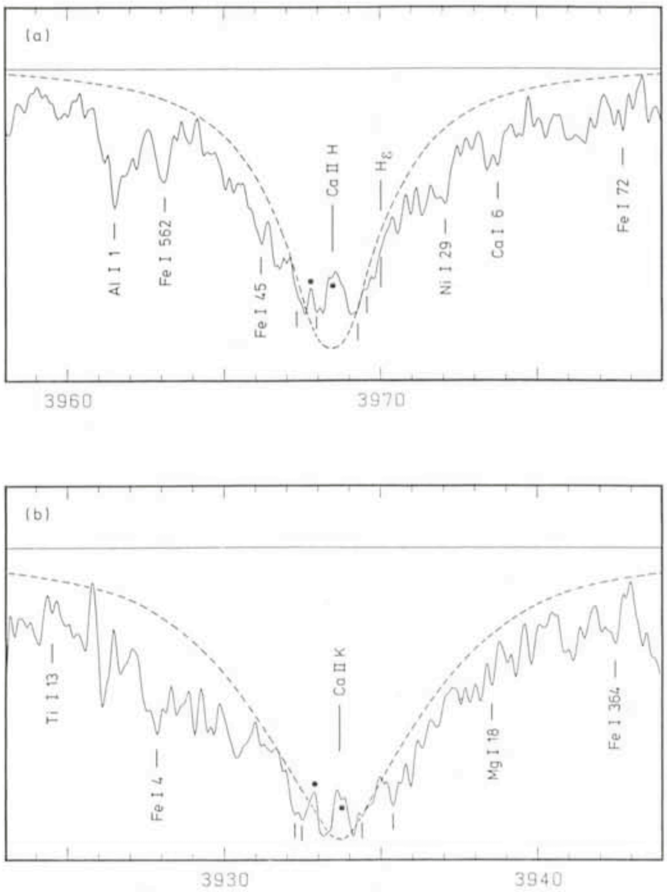

Fig. 4: *Echelle tracings of the Ca II H and K lines in HD 89499. The central emission cores are clearly visible.*

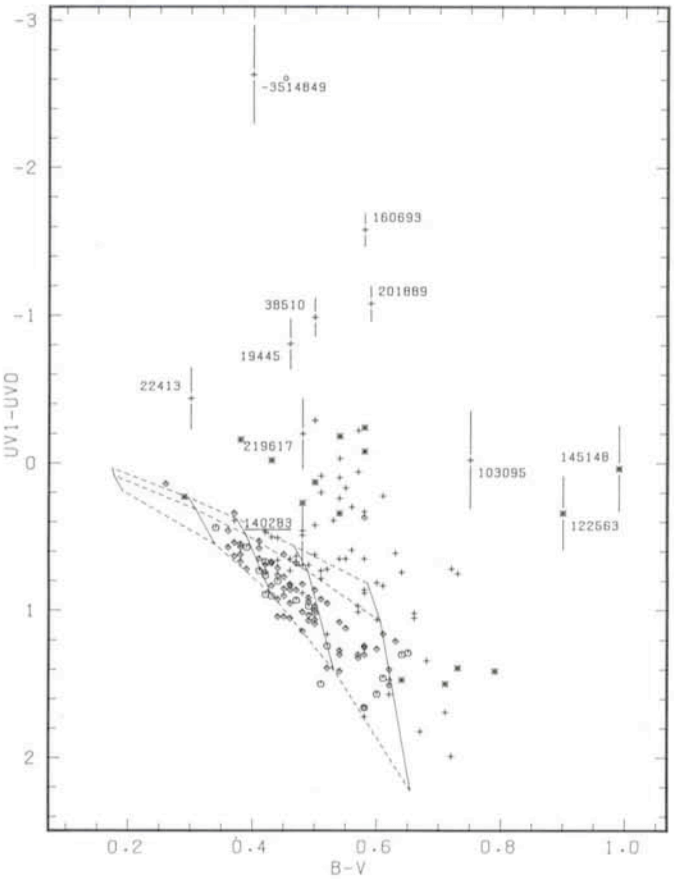

Fig. 5: *Two-colour diagram for late-type stars including all the stars in the lists of Abt and Levy (1976,* Astrophys. J. Suppl. **30,** *273, mostly population I) and Carney (1979,* A Catalogue of Field Population II Stars*), for which UV magnitudes have been measured from the TD-1 satellite. UV0 and UV1 refer to ~ 300 Å wide passbands centered on 2740 and 2365 Å, respectively. The model grid taken from Kurucz (1979) shows solid lines of constant temperature (starting with 5500 K on the right) and dashed curves of constant metal abundance (1, 0.1 and 0.01 solar from the bottom). Crosses are population II dwarfs, asterisks are population II giants or subgiants. Diamonds and circles refer to population I dwarfs and giants, respectively. Bars denote the observational errors.*

(2) Metal Abundances

Since detailed spectroscopic abundance analyses of the high-resolution observations will be published in a separate paper, we will give only a short summary of the results. According to model atmosphere analyses, iron abundances for 6 of the halo subdwarfs range from [Fe/H] = –1.3 to –2,2, generally in fair agreement with photometric predictions based on δ(U-B) or dm_1(b-y). Within the expected error limits, using solar oscillator strengths and damping parameter in differential analyses relative to the Sun, *none* of the heavy elements observed is overdeficient with respect to iron. In particular, the striking agreement in metal deficiency of odd-Z elements like ^{27}Al, ^{51}V, ^{55}Mn and ^{59}Co with ^{56}Fe definitely rules out purely explosive carbon and silicon burning in supernovae without assuming an appreciable increase of the neutron excess, η, prior to the ignition. According to Arnett (1971, *Astrophys. J.* **166,** 153), this could be achieved in a preceding stage of hydrostatic thermonuclear reactions.

Our results do not confirm the mild overdeficiency of the s-process elements Sr, Y and Zr for [Fe/H] < –1.5, found by Spite and Spite (1978, *Astron. Astrophys.* **67,** 23). However, except for the Sr II resonance lines which are strongly blended, the measured equivalent widths are very uncertain. The predicted ageing effect of s-process elements can be more readily detected by analyzing the strong Ba II lines, which are outside the spectral region we observed. For two of the subdwarfs it was possible to measure the Eu II 4129.7 line, and the corresponding abundances of the r-process element Eu are in agreement with those obtained for iron.

(3) The Peculiar Subdwarf HD 89499

The ultraviolet excess of HD 89499 is larger than that predicted for a star with zero-metal content (cf. Fig. 1). Recent photometry, combined with previously observed colours, indicates variations of Δ(U-B) ≅ 0.10 and Δ(B-V) ≅ 0.07. The echelle spectrum of this V = 8.7 mag star shows fairly broad lines with half widths 15 to 20 km/s in excess of instrumental resolution. Part of its spectrum is reproduced in Fig. 4, clearly displaying the relatively strong *emission cores* of the Ca II H and K lines. Model atmosphere analysis yields T_{eff} = 5300 K, log g = 4.25, and a fairly uniform metal deficiency of ~ 1/100 solar. Radial velocity measurements range from +6 km/s to –30 km/s and –85 km/s. Thus, there is no doubt that HD 89499 is a short-period spectroscopic binary. The Ca II line emission cores and the excessive metal line widths fit to a close binary model in which orbital and rotational velocities are coupled by tidal interaction.

(4) Satellite UV Excesses

In addition to the problems mentioned in the introduction, the ultraviolet stellar fluxes measured from the TD–1 satellite have confronted us with a surprising result: some of the metal-poor stars have UV excesses of 1 to 3 magnitudes. In Fig. 5 we have plotted a two-colour diagram in which the magnitudes UVO and UV1 refer to ~ 300 Å wide passbands centered on 2740 Å and 2365 Å, respectively. The excess is determined with respect to "normal" colours as synthesized from the grid of model atmospheres published by Kurucz (1979, *Astrophys. J. Suppl.* **40,** 1). The observed δ(UV1-UVO) by far exceed the probable uncertainties inherent to theoretical model atmospheres. While a satisfactory explanation of these strange and probably important observations has to be deferred until satellite observations with higher resolution become available, we may articulate our ignorance in a few comments:

(a) Although a moderate excess in UV1-UVO has been observed for a few population I stars, the overwhelming majority belongs to a metal-poor population (cf. Fig. 5).

(b) All the stars with excessive satellite UV fluxes also show considerable U-B excesses. However, the correlation of δ(UV1-UVO) with δ(U-B) or δm_1 is merely marginal. For instance, the colours of HD 140283, one of the most metal-poor stars known today, fit perfectly to what is expected from spectrum synthesis, whereas HD 19445, the "standard" halo subdwarf, has an excess of more than 1 mag.

(c) The observed δ(UV1-UVO) neither correlate with δc_1 (b-y), which rules out any explanation based on gravity effects. Moreover, model atmosphere computations predict a difference in UV1-UVO of less than 0.2 mag, when comparing dwarfs and giants.

(d) Except for CD –35°14849, all stars in Fig. 5 have UVO magnitudes quite in agreement with model predictions. The UVO and UV1 passbands are separated by the 2500 Å absorption edge of Mg I. However, the assumption of a peculiar Mg/Fe ratio is in contradiction to abundances derived from visual spectra of HD 19445 and HD 140283. In both passbands, the dominant source of line blanketing are low-excitation lines of Fe II, while UVO also contains the Mg II resonance lines. Thus, among very metal-poor stars, no combination of element abundances can plausibly explain the order of magnitude differences observed in the UV1 passband.

Unless the reported observations are completely unreliable, our arguments suggest an explanation outside the conventional limits of single stars.

Conclusions

The external evidence for radial velocity variability among metal-poor stars presented above, which is at variance with previous observations, would seem to deserve a more extended systematic approach, preferably with a fast radial velocity spectrometer like the CORAVEL. Whereas the results of our abundance analyses definitely rule out the possibility of producing heavy elements by purely explosive carbon and silicon burning, more observational efforts must be dedicated to the nucleosynthesis of r- and s-process elements. In order to measure reliably the equivalent widths of faint rare earth lines, a resolution of 50 to 80 mÅ and a signal-to-noise ratio of 50 to 100 would be necessary. Unfortunately, at present, these specifications cannot be attained for halo subdwarfs. HD 89499 has emerged to be the first subdwarf observed to have a close companion. Its Ca II line emission cores as well as the large satellite UV excesses observed for some metal-poor stars strongly recommend further observations in the ultraviolet.

Our report would not be complete without mentioning the support of the ESO technical staff and night assistants, who helped to ensure a successful observing run.

Faint Satellites of Outer Planets

Ch. Veillet, CERGA, Grasse

Introduction

In astronomy, as in other matters, the charm of novelty is one of the important factors that govern the choice of the observations. How many objects saw suddenly many eyes or kinds of detectors looking at them, before finding again, some months or years later, their sidereal quietness! . . . However, it is often after a long time of regular observations that they confide a (small) part of their secrets. The faint satellites of planets don't transgress this fortunately approximative rule. The deficiency in observations during many consecutive years makes the determination of their motion very difficult, and it is often too late to make up for lost time. We shall try to illustrate this fact in the next lines using the observations of the systems of Saturn, Uranus and Neptune we made in April 1981 on the Danish-ESO 1.5-m reflector.

Saturn

Except for sparse observations (like those by J. D. Mulholland with the 2.1-m reflector at McDonald Observatory, USA), the vicinity of Saturn has been poorly observed in order to look for faint satellites inside the orbits of the inner satellites. All the energies have been devoted to the rings. Suddenly, during the passage of the Earth through Saturn ring plane in 1979–80, and probably strongly incited by the Voyager flyby, the astronomers discovered many objects orbiting between the rings and Dione, i.e. at less than 45 arcseconds from the edge of the rings. If some of them are only visible while the rings are seen edge-on, the others can be observed even with an open ring, as is the case for Dione B (moving on Dione orbit) and for other bodies the observations of which remained unlinked up to our work.

The focal length and aperture of the Danish-ESO 1.5-m reflector are well suitable for a search for faint objects near a planet: Only a few minutes are necessary to record objects at magnitude 17–18 and the scale permits a good determination of the positions on the plates. You can see on Fig. 1 Dione B and a satellite moving on Thetys orbit which has been identified during an observing run at this telescope. A differential guiding has been used to follow the motion of Saturn during the exposures (less than 8 minutes) and a mask with eight circular apertures in the arms of the secondary mirror support vanes has been set at the front of the instrument in order to avoid the diffraction cross around the overexposed image of the planet which unfortunately would have been in the direction of the ring plane!).

The plates have been measured on a Zeiss measuring machine. The well-known satellites (Saturn II to VI) permitted to determine the parameters of the field around Saturn (scale, orientation, coordinates of the centre of the planet). Then the positions of the studied bodies could be obtained, and a least squares programme determines the best angular separation from Dione (or Thetys) which fits each observation. Fig. 2 shows the results obtained for the Thetys L_5 object. Its libration motion appears clearly, but the determination of its period is impossible: This satellite has not been observed at another epoch in 1981. . . .

Eight quasi-consecutive nights provided a series of positions of three faint satellites on the L_4 Lagrangian point of Saturn-Dione (Dione B) and the L_4 and L_5 points of Saturn-Thetys. This series has allowed the determination of an accurate position of the L_4 and L_5 Thetys objects, and thus to establish unambiguously the existence of one satellite at each of these points. We have also discovered a periodic variation of Dione B which can be explained by an eccentricity of about 0.012, five times the value found for Dione. An interesting point can be made after these observations: The facility in recording these objects (photographic plates at the Cassegrain focus of a reflector. . .) even with an open ring suggests the examination of old plates taken in equivalent conditions in order to get other positions or to affirm they were not present at a given epoch (for more information, cf. Ch. Veillet (1981, *Astron. Astrophys.* **102,** L5-L7). Some months later Voyager 2 observed both the Thetys objects as small rocks (50–60 km . . .).

Uranus

Going on with our trip among the planets, we stop near Uranus, planetary system forsaken by the observers for a long time. We find only a few observations from Miranda discovery in 1948 till the detection of the rings in 1977. The motion of Ariel, Umbriel, Titania and Oberon, the four "old" satellites, is quite well determined. But it is not so with the "youngest"! More than half of the available positions of this faint satellite up to 1977 cover the year following the discovery! However, an accurate determination of the motion of Miranda would permit a better knowledge of the gravitational parameters of the Uranian system: The mean motions of Ariel, Umbriel and Miranda