Giant H II Regions and the Quest for the Hubble Constant

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The search for yardsticks with which to measure cosmic distances is one of the fundamental endeavours of observational astronomy but this is a difficult task and it was not until the beginning of this century, when astronomy was already hundreds of years old, that the size of our own Galaxy could be determined. The yardstick which made this possible was the discovery, by Miss Henrietta Swan Leavitt, of a relation between the period of pulsation of Delta Cephei stars and their luminosities. The Cepheid period-luminosity relation was subsequently calibrated by Harlow Shapley who then used it together with the absolute magnitudes of RR Lyrae stars to measure the Milky Way.

Soon after the galactic distance scale was determined by Shapley, a great controversy arose as to whether the spiral nebulae, which were very well known at the time from the work of William and John Herschel and others, were galactic or extragalactic objects. The controversy was not settled until after the 100-inch Hooker telescope was brought into operation at Mount Wilson, and Hubble discovered cepheid variables in the Great Andromeda Nebula (M31) in 1924 and later in other spiral nebulae. The "island universe" hypothesis of Kant was thus proved and for the first time it was observationally established that the Universe extends far beyond the limits of the Milky Way.

Soon after the work of Hubble, several astronomers began to measure radial velocities of galaxies and discovered that these velocities increased linearly with distance. Thus, if R is the distance of a galaxy and V its radial velocity, the two are related as,

$$V = H_o \times R$$

where H_o is a universal constant. In 1931, Hubble and Humason calibrated this relationship in galaxies where they had previously found Cepheid variables and obtained a value of H_o = 558 km/sec/Mpc for this constant which is now known as the Hubble constant. Almost ten years before the work of Hubble and Humason, the Russian mathematician Alexander Friedmann had found a solution of Einstein's General Relativity equations which predicted that the Universe should be either expanding or contracting according to a linear relation between velocity and distance. Thus, immediately after Hubble's results were published, the idea that our Universe is expanding gained universal acceptance.

The Friedmann solutions have a singularity where the radius of the Universe is zero and mass density infinite. In fact the Hubble relation ($V = H_oR$) implies that some time in the past all galaxies were on top of each other. For obvious onomatopoeic reasons the singularity is called the "Big-Bang"; thus the singularity is interpreted as a magnificent cosmic firework which marked the beginning of time. Friedmann cosmologies can be parametrized in terms of the expansion rate H_o, the mass density Ω_o, and an elusive parameter called the cosmological constant, Λ, which has bedeviled cosmology since it was first introduced by Einstein himself.

Einstein's theory allows for the existence of this additive constant which represents either an additional attractive or repulsive "gravitational" force but there is no compelling reason in the general theory of relativity for this force to exist in nature. It is merely allowed by the mathematical structure of the equations. Einstein found that in order to construct a statical model for the Universe, he had to introduce a repulsion term to balance gravity. Of course, in 1917 everybody, including Einstein, thought that the Universe was static!

With no cosmological constant (Λ = 0), Friedmann's models give simple relationships between the age of the Universe (T_o, the time elapsed since the Big-Bang) and the Hubble constant and Ω_o. In general T_o is always smaller than H_o^{-1} and it is equal to H_o^{-1} if the mass density is zero ($\Omega_o = 0$).

Thus, the calibration of the Hubble relation provides not only the most powerful cosmic yardstick but also a means of determining the age of the Universe. It is not yet known how important the deceleration and the gravitational repulsion terms in Friedmann models are but, at least in principle, they can be determined observationally and this is one of the major tasks of modern observational cosmology. An important constraint on the Hubble constant is that, for $\Lambda = 0$, H_o^{-1} must be larger than the age of the Galaxy. At the time of Hubble's work, this limit was the age of the earth, about 4,000 million years. Today, from the theory of stellar evolution and from observations of globular clusters the age of our galaxy is estimated to be more than 16,000 million years.

The Determination of H_o

Periods and luminosities of Cepheids can be reliably determined from the ground out to distances of about 5 Mpc. One of the major tasks of the Hubble Space Telescope will be to extend these observations to larger distances. Our Milky Way is a member of a group of galaxies (the Local Group) of roughly 1 Mpc in diameter of which the Andromeda nebula is also a member. The Local Group is itself member of a larger agglomeration of galaxies known as the Local Supercluster which is dominated by the Virgo cluster, distant 15–20 Mpc from the Local Group. Thus, the expansion of the Universe is perturbed at small distances by these mass concentrations and it is necessary to measure velocites and distances to galaxies beyond the Virgo cluster in order to derive a meaningful value for the Hubble constant. Hubble's own determination was too large because of a number of errors, including a large error in Shapley's calibration of the cepheid period-luminosity relation. But even today, almost 60 years after the pioneering work of Hubble and Humason, astronomers have not yet agreed on the exact value of H_o although most agree that it lies between 50 and 100 km/sec/Mpc. In fact, the opinions are divided in two groups; the H_o = 50 camp championed by Sandage and Tammann, and the H_o = 100 camp whose strongest advocates are Aaronson and co-workers and G. de Vaucouleurs. Both camps defend their cause with excellent observations but the controversy is still far from being resolved. The discrepancy is also philosophical; at H_o = 50, the Big-Bang age of the Universe is consistent with the age of the oldest stars in our Galaxy while for H_o = 100 that age is too short and, in order to maintain consistency with the Friedmann models, the cosmological constant must be revived.

In this article I would like to present a new method (in fact a new version of an old method), developed in collaboration with Roberto Terlevich from the RGO and Mariano Moles from the IAA in Granada, which uses the properties of giant H II regions as distance indicators.

Giant H II Regions as Distance Indicators

In the early 1960s Sersic discovered that the diameters of the largest H II regions in spiral galaxies increase with galaxy luminosity. This correlation was further developed by Sandage and it has since been used by many workers as a cosmic yardstick. The correlation, however, is not useful much beyond

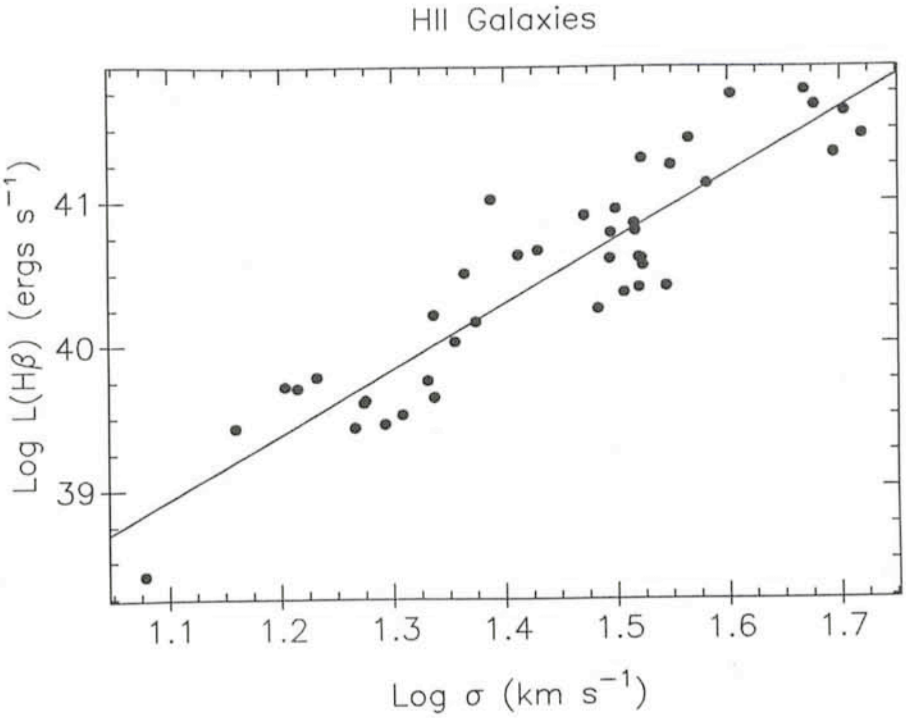

Figure 1: *Logarithmic plot of the integrated H_β luminosities of HII galaxies as a function of their line-profile widths in velocity units. H_o = 100 km/sec/Mpc is assumed.*

20 Mpc where the angular diameters of even the largest giant HII regions become comparable with the seeing disks. However, the linear diameters of giant HII regions correlate very well with the widths of the nebular emission lines, which in these bright HII regions are extremely easy to measure.

Thus, replacing HII region diameters by line-widths in the Sersic-Sandage correlations, a new powerful distance indicator is obtained. However, the emission line profile widths also correlate extremely well with the luminosities of giant HII regions and this correlation has the advantages (over the previous ones) that it does not require inclination corrections for the magnitudes of the parent galaxies and that the reddening corrections to the giant HII region luminosities can be done in a self-consistent way using the Balmer decrements. Thus, the method I am going to discuss here relies on the correlation between H_β luminosity ($L(H_\beta)$), the emission line-profile widths (σ) and the Oxygen abundances (O/H) of giant HII regions.

Since, to obtain a meaningful value of H_o, we must observe galaxies beyond the Virgo cluster we have applied the method not to giant HII regions in distant spiral galaxies (which would be too faint) but to the so-called "intergalactic HII regions" or "HII Galaxies" which may be defined as being dwarf galaxies with the spectrum of giant HII regions. In fact, while some HII galaxies are clearly dwarf irregular galaxies with one or more extremely luminous giant HII regions, others are essentially star-like objects where only the giant HII region component is visible and are probably truly intergalactic, galaxy-size HII regions. Figure 1 presents a log plot of $L(H_\beta)$ versus σ for a sample of HII galaxies for which the luminosities have been obtained with the 3.6-m and 2.2-m telescopes at La Silla and the line-widths with the Echelle spectrograph at the 4-m telescope of Cerro Tololo.

The slope of the correlation is 4.5 ± 0.3 and rms scatter is $\delta \log L(H_\beta) = 0.32$ but the dispersion is correlated with the chemical composition of the nebular gas. A Principal Component Analysis of the data leads to the following relation.

$$\text{Log } L(H_\beta) = 5 \log\sigma - \log(\text{O/H}) + \text{constant}$$

Figure 2 presents a plot of $L(H_\beta)$ versus the distance independent parameter $Mz = \sigma^5/(\text{O/H})$ for 29 HII galaxies with accurate metallicities.

The linear fit to the data has a slope of 1.03 ± 0.05 and an rms scatter of $\delta \log(L(H_\beta)) = 0.21$, which is comparable to the scatter of the Tully-Fisher relation. Since HII galaxies can be easily observed out to very large distances, the correlation between $L(H_\beta)$ and Mz can indeed be a very useful cosmic yardstick provided its zero point can be accurately determined.

As I discussed above, the extragalactic distance scale is tied to the galactic scale via cepheid variables. Thus, in order to calibrate the zero point of the ($L(H_\beta)$, Mz) relation for HII galaxies we must use giant HII regions in nearby spiral galaxies. The properties of many such HII regions have been extensively studied mainly by Sandage and Tammann who used the Sersic-Sandage correlation to calibrate distances.

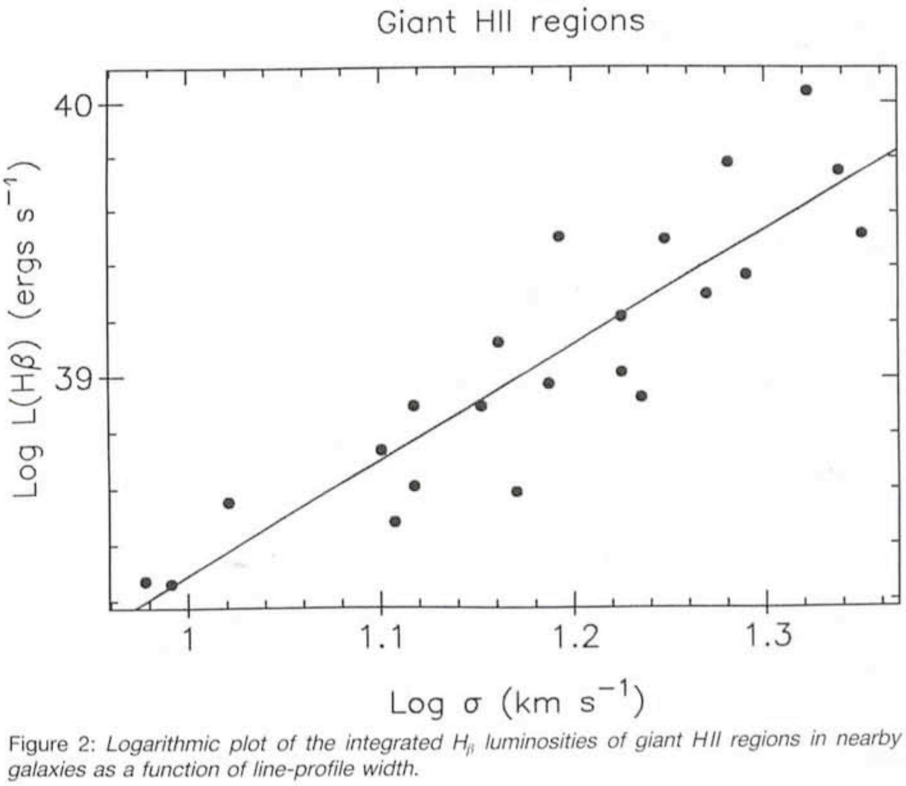

Figure 2: *Logarithmic plot of the integrated H_β luminosities of giant HII regions in nearby galaxies as a function of line-profile width.*

TABLE 1: *The local distance scale*

Galaxy	Number of H II regions	Distance adopted	(Kpc) ST	Notes
LMC	1	50.1	52.2	Local Group
SMC	1	60.0	71.4	Local Group
NGC 6822	2	457	616	Local Group
M 33	4	682	817	Local Group
NGC 2366	3	3160	3250	M81 group
NGC 2403	3	3160	3250	M81 group
Holmb II	1	3160	3250	M81 group
IC 2574	2	3160	3250	M81 group
NGC 4236	2	3160	3250	M81 group
M101	3	6920	6920	

We have studied the correlations between internal parameters for 22 giant H II regions in galaxies whose distances have been determined from studies of Cepheid variables. Table 1 summarizes the relevant parameters of these galaxies together with the distances we have adopted. Also listed in the Table are the distances adopted by Sandage and Tammann (ST) in their calibration of the Hubble constant.

In a few cases there are differences between the scale adopted here, which is essentially the scale adopted by Aaronson and co-workers in their calibration of the Tully-Fisher relation, and the Sandage-Tammann scale. These discrepancies have to do with the way in which the Cepheid luminosities are corrected for extinction in their parent galaxies and, although the local distance scale is still the subject of considerable controversy, its discussion is far beyond the scope of this article.

Figure 3 shows a logarithmic plot of $L(H_\beta)$ versus σ for giant H II regions. The slope of this relation if 4.2 ± 0.5 and the rms scatter is $\delta \log (L(H_\beta)) = 0.23$.

A Principal Component Analysis (PCA) for H II regions shows again the presence of 3 parameters of the form,

$$\text{Log } L(H_\beta) = \text{Log } RC\, \sigma^2 - \text{Log}(O/H) + \text{constant}$$

where Rc is a measure of the radius of giant H II regions introduced by Sandage and Tammann which they called the core radius. This relation cannot be directly compared with H II galaxies because we lack core radii for these distant objects. However, in giant H II regions, the core radii corelate with velocity dispersion approximately as $Rc \sim \sigma^3$. Thus, the parameter $Rc\, \sigma^2$ is equivalent to the parameter σ^5 which we found for H II galaxies. Indeed, the PCA analysis of H II galaxies in the ($L(H_\beta)$, σ^5, O/H) domain and of giant H II regions in the ($L(H_\beta)$, $Rc\,\sigma^2$, O/H) domain give essentially identical eigenvalues and eigenvectors.

This leads us to conclude that, independently of the mass of the parent galaxies, the global luminosities of giant H II regions are a function only of their velocity dispersion, radii and chemical composition. Moreover, the $RC\,\sigma^2$ dependence is strongly reminiscent of the Virial theory and Terlevich and I have proposed that giant H II regions are gravitationally bound objects, in which case the correlations would have a very simple physical interpretation. But, as almost everything in astronomy, this interpretation is controversial and its discussion will take us far from our present goal of getting to H_o.

From the ($L(H_\beta)$, Mz) relation for giant H II regions we obtain a zero point of 41.32 ± 0.08 and therefore the cosmic yardstick for H II galaxies is the equation,

$$\text{Log } L(H_\beta) = \text{Log } \frac{\sigma^5}{(O/H)} + 41.32$$

The distances for H II galaxies can then be obtained by comparing the luminosities predicted by this equation to the observed fluxes corrected for extinction. Before discussing the results, however, I must say a few words about radial velocities and about Malmquist bias.

Corrections . . .

(a) The Radial Velocities

If one knows velocities and distances, H_o is simply obtained as $H_o = V/R$. The radial velocity of almost any galaxy can be easily obtained with present-day instrumentation from the Doppler shift of their spectral features. In the case of H II galaxies, for example, even at large distances the Doppler shifts of the emission lines can be obtained with exposures of only a few seconds. However, the Earth, the Sun and the Galaxy are moving and therefore we must subtract from the observed velocities the motion of our frame of reference. Thus, we must remove the motions of the Sun around the centre of our Galaxy, of the Galaxy in the Local Group, of the Local Group towards the Virgo Cluster and of the Virgo Cluster relative to the Cosmic Microwave Background. In addition, the galaxies themselves may be falling into Virgo or drifting relative to the Cosmic Microwave Background and these peculiar velocities must also be removed to extract the purely expansional velocities. Our radial velocities incorporate all these corrections with the exception of streaming motions relative to the Microwave Background which at

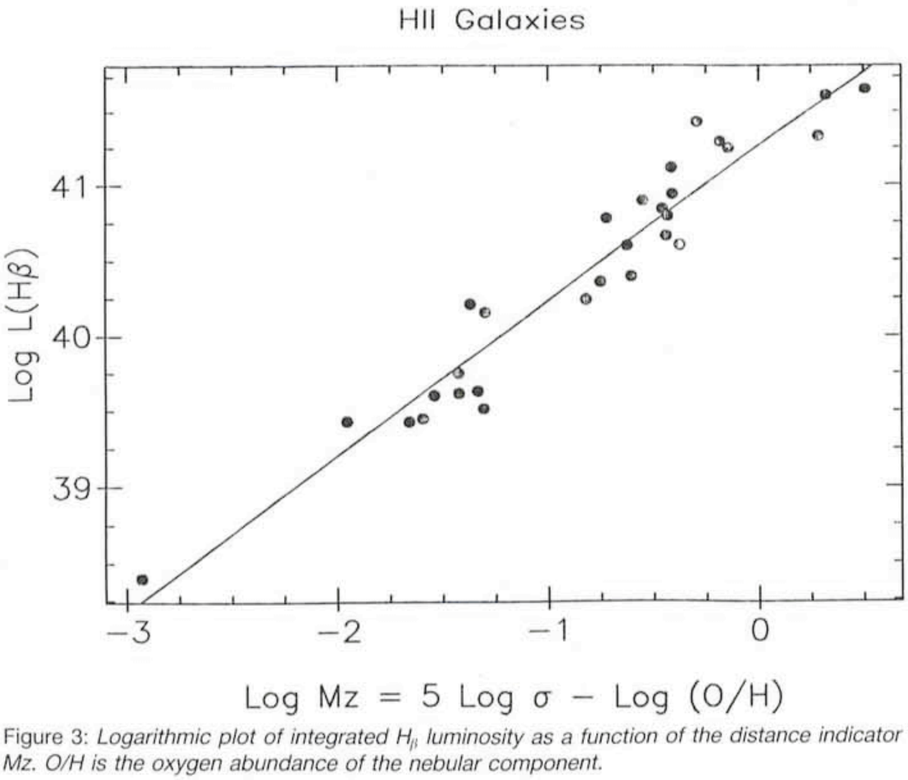

Figure 3: *Logarithmic plot of integrated H_β luminosity as a function of the distance indicator Mz. O/H is the oxygen abundance of the nebular component.*

present are very poorly understood. The most recent results tend to show that as far as they can be observed, all galaxies move relative to the CMWB with a velocity of several hundred kilometres per second in the direction of Centaurus. Thus, it is not clear at what distance one should start correcting the velocities for this effect or if one should correct them at all!

TABLE 2: *The Hubble constant*

Redshift range	$\langle H_o \rangle$ km/sec/Mpc	Malmquist correction	Number of galaxies
Full sample	94 ± 5	−11	29
Excluding Virgo	97 ± 5	−12	24
Redshift > 2000	99 ± 5	−14	21
Redshift > 4000	102 ± 6	−16	16

(b) Malmquist Bias

This is an unpleasant effect which has caused and continues to cause endless troubles to those who engage in the quest for the Hubble constant. Malmquist bias occurs because all correlations used to determine distances have considerable cosmic scatter. So if one selects galaxies which are brighter than a certain limiting value, close to this value one tends to observe galaxies which are systematically brighter than the luminosities one would predict from the distance indicator in the absence of bias. This causes the distances to be biased towards lower values.

I am very fortunate to have Edmond Giraud ("Mr. Malmquist Bias") next doors who showed me how to correct magnitude limited samples for this effect. Because at any distance H II galaxies span a very large range of luminosities, and because there are luminous H II galaxies at small distances, the Malmquist effect on the distance indicator is, as we shall see, very small.

The Hubble Constant from Giant H II Regions

The resulting values for H_o are given in Table 2 for different redshift cuts of the data.

The errors quoted are 1 σ deviations from the mean of all galaxies and do not include the zero point error. When this is included, our best estimate is $H_o = 85 \pm 10$ km/sec/Mpc. this value compares very well with the value of $H_o = 92 \pm 1$ found by Aaronson and co-workers using the Tully-Fisher relation (the error they quote does not include zero point uncertainties). Our value disagrees with the value of $H_o = 50 \pm 7$ km/sec/Mpc obtained by Sandage and Tammann. If we use the Sandage-Tammann local distance scale (Table 1) we obtain a value of 78 ± 10 which still disagrees at the 3 σ level with $H_o = 50$.

Caveats

Recently, a well-known cosmologist told me: "Your results are very nice, so . . . what's wrong with them?" What he meant, of course, was that I had obtained the wrong value for H_o. This illustrates the philosophical prejudices involved in cosmology; this is only natural because Cosmology reaches the boundary between science and religion. Personally, I find the story of Adam and Eve more elegant and easier to believe than the Big-Bang!

Nevertheless, observers must forsake philosophical and theoretical prejudices in the analysis of the weak points of our own data. In the case of giant H II regions, the caveat is that the H_β luminosities of some H II galaxies may come from more than one giant H II region superimposed along the line of sight. This would not only bias the luminosities towards larger values but also introduce the gravitational potential of the parent galaxies as an additional parameter. As far as we can tell from deep CCD pictures and spatially resolved spectroscopy, the effect of multiplicity in our sample is small. The fact that the scatter of the H II galaxy correlations is similar to that exhibited by the giant H II region sample lends strong support to this conclusion.

It is clear, however, that if the emission-line component of all H II galaxies consisted of four identical giant H II regions of exactly the same redshift superimposed along the line of sight we would not distinguish them from single objects but our value of H_o would be overestimated by a factor of 2!

Epilogue

A large value of H_o is only one of a number of new observations which are beginning to erode the old edifice of Big-Bang cosmology. Inflation, dark matter, superstrings and other scaffoldings are being used to save the "standard" Big-Bang but in the end it will surely fall. This should not worry us, for we know that new buildings are always more solid than old structures. Unfortunately, however, there are very few modern buildings that are nicer than the old ones they replace.

References

For the sake of brevity I have not included formal references to the work I quoted. I have based the discussion on the following works where complete lists of references can be found:

(1) R. Kippenhahn: *Light from the Depths of Time* (Springer) for the history of the Hubble constant.
(2) A. Sandage: "The Dynamical parameters of the Universe", in First ESO/CERN Symposium, *Large Scale Structure of the Universe, Cosmology and Fundamental Physics*, p. 127, for a modern account of the quest for the Hubble constant and the defence of $H_o = 50$.
(3) M. Aaronson and co-workers in *Astrophysical Journal* Vol. **302,** p. 536 (1986) for a detailed discussion of the Tully-Fisher method, the various radial velocity corrections and a defence of the $H_o = 100$ view.
(4) J. Melnick and co-workers in ESO preprint number 440 (1986) for a discussion of the use of giant H II regions as distance indicators.

Visiting Astronomers

(April 1–October 1, 1987)

Observing time has now been allocated for Period 39 (April 1–October 1, 1987). 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: Martinet/Jarvis/Pfenniger/Bacon, Franx/Illingworth, Ilovaisky/Chevalier/v. d. Klis/v. Paradijs/Pedersen, Mathys/Stenflo, François/Spite M/Spite F, Jeffery/Hunger/Heber/Schönberner, Hunger/Heber/Werner/Rauch, Miley/Macchetto/Heckman, Kollatschny/Fricke, Maccagni/Vettolani.

May: Maccagni/Vettolani, Keel, Ortolani/Rosino, Cacciari/Clementini/Prévot/Lindgren, Barbuy/Ortolani/Bica, Gratton/Ortolani, Lub/de Geus/ Blaauw/de Zeeuw/Mathieu, Cacciari/Clementini/Prévot/Lindgren, Moorwood/Oliva, Danziger/Oliva/Moorwood, Tapia/Persi/Ferrari-Toniolo/Roth, Lacombe/Léna/Rouan/Slezak.

June: Lacombe/Léna/Rouan/Slezak, Chelli/Reipurth/Cruz-G., Richichi/Salinari/Lisi, Zinnecker/Perrier, Perrier/Mariotti, Habing/van der Veen, Sicardy/Brahic/Lecacheux/