Rev. Mexicana Astron. Astrof., **19**, 92-98 (1989)

OBSERVATIONAL COSMOLOGY IN THE SOUTHERN SKY

H.W. Duerbeck, R. Duemmler, H. Horstmann, H.-A. Ott,
P. Schuecker, W.C. Seitter, D. Teuber, and H.-J. Tucholke

Astronomisches Institut der Universität Münster

RESUMEN. El proyecto Muenster de corrimiento al rojo estudia la distribución tridimensional de un gran número de galaxias y usa los resultados para derivar parámetros cosmológicos y propiedades de estructuras a gran escala en el universo. Se da una breve descripción de los métodos y se presentan resultados preliminares.

ABSTRACT. The Muenster Redshift Project (MRSP) studies the three- dimensional distribution of large numbers of galaxies and uses the results to derive cosmological parameters and properties of large-scale structures in the universe. Brief descriptions of the methods are given and preliminary results presented.

Key words: **COSMOLOGY – GALAXIES-EVOLUTION – GALAXIES- REDSHIFTS**

1. Introduction

Modern observational cosmology has two aspects. One concerns the *cosmological parameters* which describe the universe-at-large by linking relativistic cosmology, through which they are defined, to observations; the other concerns *large-scale structures* in the universe, which provide clues to processes that occurred in the very early universe and to the evolution of structures up to their present state. The *cosmological parameters* rest on the assumptions of the cosmological principle – large-scale homogeneity and isotropy in the mass distribution. They are the Hubble constant H_0, the deceleration parameter q_0, the density parameter Ω_0 and the cosmological constant Λ. The *large-scale descriptors* are measures of the *structured* distribution of luminous matter on scales smaller than the whole – galaxies, clusters of galaxies and superclusters, separated by large voids; they are expressed in terms of correlation functions, luminosity functions, void probability functions, fractal dimensions and other statistical parameters.

Hierarchical systems of stellar matter were first proposed, in 1750, by Thomas Wright of Durham, later taken up by several investigators and mathematically formulated by Charlier in 1922. Observations of nebulae, the building blocks of Wright's universe (except for those which much later were recognized as members of our own stellar system), accumulated from the first catalogues of Messier and Méchain (since 1771), increased fiftyfold due to the untiring efforts of one family, the Herschels (since 1786), and culminated in extensive catalogues of galaxies, clusters of galaxies and superclusters of galaxies. The 1970s mark the transition to automation and the extension of observational emphasis to the southern hemisphere. In fact, the ESO-SRC Atlas (since 1975) has provided material for the first catalogues of galaxies obtained by automated procedures. Four million galaxies have been measured up to now in two dimensions to the limit of $m_J = 21$, largely due to the efforts of groups in Cambridge, UK (Maddox *et al.* 1988) and to the Edinburgh-Durham collaboration (Heydon-Dumbleton *et al.* 1988). Fig. 1a shows the number of measured galaxies as a function of date.

The third spatial dimension became available when it was recognized that redshifts measured in galaxy spectra have a *cosmological component*, as found by de Sitter 1917 and followers. After proper subtraction of Doppler shifts due to individual galaxy motions, the redshifts locate galaxies in the depth of space. The rate of exponential growth of known redshifts since the first measurements by Slipher in 1912 relates to the growth of two-dimensional galaxy positions during the same period as 1.4 : 1, Fig. 1b. Nevertheless, at

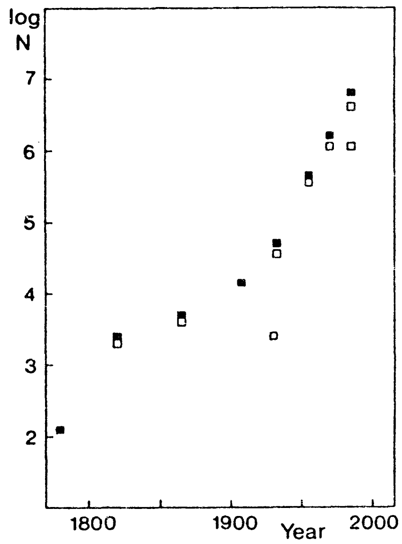

Fig. 1a. The increase in number of identified galaxies from the late 18th to the late 20th century. Open symbols: individual catalogues; filled symbols: cumulative data.

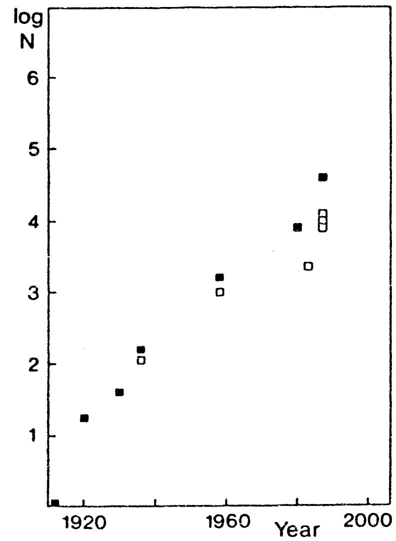

Fig. 1b. The increase in number of measured redshifts from 1912 to 1987. Open symbols: individual catalogues; filled symbols: cumulative data (Seitter 1988).

present only one redshift per 150 galaxies is known. The largest single contributions come from the Center for Astrophysics (Huchra 1983, 1986).

2. The MRSP

In order to significantly increase the number of measured redshifts, the Astronomical Institute in Muenster started the "Muenster Redshift Project" (MRSP) in 1986. Pairs of film copies of direct plates of the ESO-SRC Atlas and low-dispersion objective prism plates from the UK-Schmidt telescope are used to determine fully automatically two-dimensional relative positions ($\sigma_{x,y} = 0''.07$), absolute positions ($\sigma_{\alpha,\delta} = 0''.2$, including catalogue errors), and redshifts of medium accuracy ($\sigma_z = 0.01$).

The rationale of the project is based on the experience that large numbers of objects measured at large distances with medium accuracy convey more cosmological information than high accuracy measurements, which are presently restricted to our immediate cosmological neighbourhood, and/or small numbers, and may be severely influenced by systematic errors. At distances of the order $z = 0.1$, the known ranges of Doppler motions contribute generally less than 3% systematic error to the measured redshifts. The large numbers of objects permit the use of complete subsamples, thus avoiding sampling errors, and/or leading to highly reliable correction terms, while the large numbers make the standard errors very small. The present limits of the MRSP are $m_J = 19.7$ and $z = 0.3$. The total number of redshifts measured to date is 40 000.

3. Reduction Methods

Reduction methods used in the MRSP for both two-dimensional and three-dimensional investigations are described in detail in a series of papers by Horstmann (1988), Schuecker (1988 a,b), Tucholke (1988), and Gericke (1988); additional information is found in Seitter *et al.* (1989). The communications concern scanning procedures with the PDS 2020GM^{plus} and fully automatic reduction programs for: image restauration, position determination, star-galaxy separation, removal of double stars and artefacts, coarse morphological classification of galaxies, measurement of wavelength reference points, determination of redshifts, transformation of density to intensity for spectral energy distributions and stellar and galaxy magnitudes, magnitude corrections for systematic exposure effects, spectral classification and selection of quasar candidates.

Major steps in redshift determination are the following. A spectral continuum suitable to locate the calcium break (caused by the unresolved Ca II doublet near 400 nm) is defined using fuzzy set algebra. The red sensitivity cutoff of the J-emulsion is used as a preliminary wavelength zero point for approximately 1000 G-K stars (per plate) in the same magnitude range (to avoid colour and exposure effects). The transformation equation from the direct plate to the objective prism plate is obtained by using the position of the undisplaced Ca II feature in the G-K stars as reference position. The transformation provides the predicted undisplaced positions of Ca II for all objects and thus the zero point for wavelength measurements. For spectral classification of the G-K stars fuzzy set algebra is used.

Identification of the calcium break uses slope criteria. The difference between the expected break position for zero redshift in the galaxy spectrum and the measured break yields the redshift. Besides the break measuring method two additional procedures are employed: cross correlation of the line spectrum with a suitable template, and matching of the total intensity distribution with an artificially redshifted spectrum. The cross correlation method yields the best results. 90% of the redshifts are obtained from at least two methods. The error $dz = 0.01$ is both the internal error for single measurements using the differences of results from the three methods, and the external error derived from the (presently) small number of high quality redshifts found in the fields.

4. First Results

4.1 Structure of the Universe

Large numbers of redshifts, together with magnitude measurements, can be used to determine the *Hubble constant* by a statistical method, which does not depend on velocity measurements from relatively nearby galaxies. The *acceleration parameter*, determined by a modified redshift-volume test, yields the gravitational effects due to both luminous and dark matter and to the unknown contribution of Λ. Reductions which include the *cosmological constant*, whose accelerating or decelerating power must as yet be measured, are in progress. In a volume

$$V = 10^7\, h^{-3}\ \mathrm{Mpc}^3 \tag{1}$$

the mean density of luminous matter is derived from the luminosity function of all 40 000 galaxies. The luminosity functions of high density regions (clusters) and low density regions (fields) merge sufficiently well to consider the presently available luminosity function a *general luminosity function* for the volume surveyed so far. Our present value, assuming $(M/L)_{\mathrm{B}} = (35\ldots 50)\, h\, (M/L)_{\odot}$ (Faber and Gallagher 1979), is

$$\Omega_0 = 0.02\ldots 0.03\ . \tag{2}$$

Fig. 2 shows the luminosity function (LF) from which Ω_0 is derived.

The determination of the Hubble constant makes use of the fact that a well calibrated LF (measured in our vicinity) may be superimposed on uncalibrated LFs observed at large distances. From this we obtain the differential distance moduli and thus the distances of the objects contributing to the observed LFs. With the help of their redshifts, which are largely unaffected by local motions, the Hubble constant is determined. The method is an extension of the distance determination suggested by Schechter and Press (1976), but the availability of individual distances for all objects makes it unnecessary that they belong to a physical group or cluster. At the same time, the method is self-testing, because the coincidence in shape shows whether there is evolution of the LF or not, while evolution of individual galaxies is not excluded. Preliminary results, obtained by using the currently "best" values for the distance modulus of the Virgo cluster (van den Bergh 1988) are given in Table 1 (see also Seitter *et al.* 1989). Fig. 3 illustrates the corresponding luminosity functions in the given z-ranges.

Table 1. The Hubble constant in km s^{-1} Mpc^{-1} determined at different redshifts z and three values for the Virgo distance modulus used for calibration, $q_0 = 0.5$.

z	$H_0\,(31.0)$	$H_0\,(31.35)$	$H_0\,(31.7)$
0.10	75.7	64.5	54.9
0.11	77.6	66.0	56.2
0.12	78.7	67.0	57.0

The redshift-volume test for the determination of q_0 requires, as usual, that the number of galaxies per comoving volume remains constant and that differences in density may be attributed to changes in the geometry of the proper volume. Individual luminosity evolution of galaxies is permitted if it occurs at random and does not change the LF. Our method only assumes a *constant* LF over the observed z-range, without specifying its shape, due to the fact that we count galaxies in bins of *absolute* rather than apparent magnitude. A preliminary result (Ott 1988) is

$$q_0 \leq 0.25 \tag{3}$$

(confidence limit 1σ).

It should be noted again that q_0 includes the effects of both luminous and dark matter. The value is derived from a subsample of only 1000 redshifts, while computer simulations indicate that such small numbers may cause systematic effects. For reliable values one needs the input of 10^5 to 10^6 redshifts (for realization see Sect. 5).

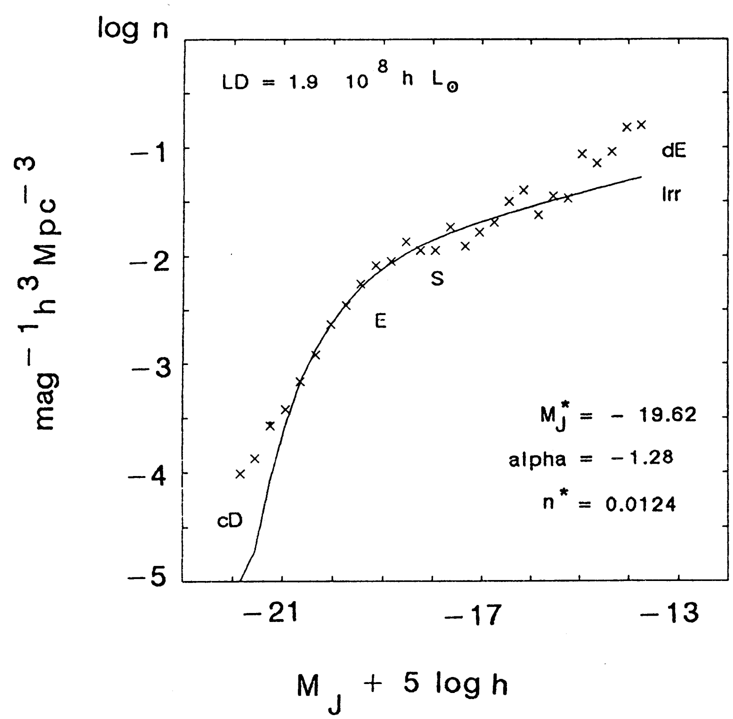

Fig. 2. The general luminosity function obtained from 40 000 galaxies in the vicinity of the South Galactic Pole up to $z = 0.3$. Deviations from the Schechter fit seem to be real. The letters indicate galaxy types, the lower inserts are the parameters of the Schechter fit (line), the upper insert gives the mean luminous density (Schuecker 1989).

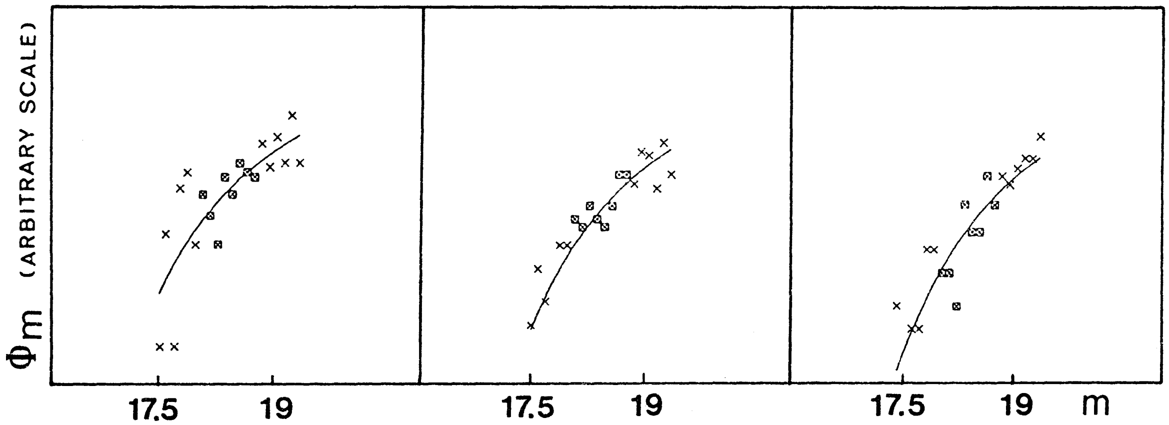

Fig. 3. Apparent luminosity functions obtained in ESO-SRC field No. 411 at three different redshifts $z = 0.10$, $z = 0.11$, $z = 0.12$. Crosses are from regions where large corrections for incompleteness were applied, they carry single weight; squared crosses are from regions where small corrections were applied, they carry double weight (Seitter *et al.* 1989).

4.2 Structures in the Universe

Mass concentrations on scales of clusters of galaxies, superclusters, and possibly super-superclusters have been located by the MRSP. The clusters are rich in elliptical galaxies and, in rare cases, in spirals. An unusually large supercluster of galaxies is found in Sculptor at $z = 0.105$. Its core contains several rich clusters, connected by bridges, while the whole supercluster extends over at least 55 h^{-1} Mpc. The core clusters show extensive substructure. Simulations indicate that this is a sign of comparative youth. Observations concerning segregation – also connected with gravitational cluster evolution – are inconclusive so far. Two other superclusters in the same area and found at $z = 0.14$ and 0.15 are separated from the nearer supercluster and from each other in three-dimensional space by distances of the order 100 h^{-1} Mpc, a finding which suggests the existence of a still larger configuration – a super-supercluster.

Evolution of large-scale clustering is indicated in Fig. 4. The β-parameter is defined as

$$\beta = \frac{< N >}{< \Delta N^2 >} \tag{4}$$

where $< N >$ is the mean number of objects in a given volume and $< \Delta N^2 >$ the variance. In gravithermodynamic theory the b-parameter (Saslaw and Hamilton 1984) measures the ratio of surplus potential energy to kinetic energy in a given sample and is related to β as $b = 1 - \sqrt{\beta}$. Presented are the β-values determined in the MRSP for galaxies and quasars, the highly uncertain values for the X-ray background estimated from the data of Gursky and Schwartz (1977), and the upper limit for structuring in the CMB (Wilkinson 1988), on mass scales equivalent to present-day galaxies.

5. Prospects

With well-tested reduction methods and powerful computers, it has become our realistic goal to measure up to half a million redshifts over the next two years. They will enable us to increase the accuracy of cosmological and structural parameters significantly. Additional work will concentrate on better calibrations, such as measurements of more high accuracy spectra to determine the external errors with higher confidence. The derivation of "spectral" sequences for quasars with the aid of high resolution observations will facilitate the identification and statistical investigation of certain quasar classes (e.g. Lyman α-quasars) without the necessity for follow-up observations.

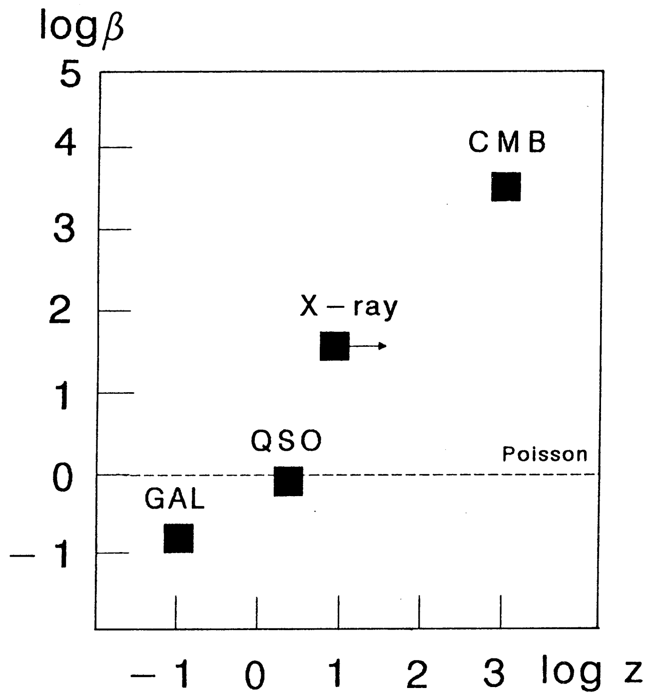

Fig. 4. Evolution of clustering for galaxy-size masses. The distribution of matter measured by the parameter β (see text) evolved from great regularity at $z = 1000$ (CMB) through Poisson distribution (at an epoch slightly earlier than quasars) to almost hierarchical clustering (galaxies) at $z = 0.1$ (Schuecker *et al.* 1989).

A particularly important calibration concerns the distance moduli of nearby clusters and groups of galaxies, a task which must largely rely on HST measurements. Other quantities for which new data are urgently needed are the M/L ratios of different structures.

In order to extend the MRSP to larger distances and earlier (evolutionary) times we shall use superpositions of digitized plates (≥ 10 plates). Tests have shown that we may expect to reach $m_{\rm R} \leq 25$. With superpositions of *spectral plates* (still to be tested) we hope to reach redshift $z \approx 0.6$, a value which corresponds to the faintest clusters seen on our plates so far.

A wide field of additional studies concerns methods of "sharpening" error-distorted structures. Various deconvolution and rectification methods will be investigated.

The derivation of structural parameters of galaxies beyond correlation functions and simple mapping requires the use of high level computer languages (AI), while *all* reduction programs benefit from the *object-oriented* environment GAME (Generic Applications and Monitors Environment, Teuber 1988, Teuber *et al.* 1989) into which all application programs are embedded.

Acknowledgements

We thank the staff of the UKSTU, Edinburgh, for kindly supplying film copies of objective prism plates and the Deutsche Forschungsgemeinschaft for generous support.

References

Faber, S.M., Gallagher, J.S. 1979, *Ann. Rev. Astr. Astrophys.* **17**, 135.

Gericke, V. 1988, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 235.

Gursky, H., Schwartz, D.A. 1977. *Ann. Rev. Astr. Astrophys.* **15**, 541.

Heydon-Dumbleton, N.H., Collins, C.A., MacGillivray, H.T. 1988, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 71.

Horstmann, H. 1988, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 111.

Huchra, J.P. 1983, unpublished redshift compilation.

Huchra, J.P. 1986, unpublished redshift compilation.

Maddox, S.J., Loveday, J., Sutherland, W.J., Efstathiou, G. 1988, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 90.

Ott, H.-A. 1988, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 125.

Saslaw, W.C., Hamilton, A.J.S., 1984. *Astrophys. J.* **276**, 13.

Schechter, P., Press, W.H. 1976, *Astrophys. J.* **203**, 557.

Schuecker, P. 1988a, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 142.

Schuecker, P. 1988b, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 160.

Schuecker, P. 1989, to be published.

Schuecker, P., Ott, H.-A., Horstmann, H., Gericke, V., Seitter, W.C. 1989, in Proc. Third ESO-CERN Symposium, (Dordrecht: Kluwer), in press.

Seitter, W.C. 1988, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 9.

Seitter, W.C., Ott. H.-A., Duemmler, R., Schuecker, P., Horstmann, H., 1989, in *Morphological Cosmology*, eds. P. Flin and H.W. Duerbeck, Lecture Notes in Physics 332 (Berlin: Springer), p. 3.

Teuber, D. 1988, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 323.

Teuber, D., Schuecker, P., Horstmann, H. 1989, in *Knowledge-Based Systems in Astronomy*, eds. A. Heck and F. Murtagh, Lecture Notes in Physics 329 (Berlin: Springer), p. 53.

Tucholke, H.-J. 1988, in *Large-Scale Structures in the Universe – Observational and Analytical Methods*, eds. W.C. Seitter, H.W. Duerbeck and M. Tacke, Lecture Notes in Physics 310 (Berlin: Springer), p. 136.

van den Bergh, S. 1988, in *The Extragalactic Distance Scale*, eds. S. van den Bergh and C.J. Pritchet, ASP Conf. Ser. 4 (San Francisco: Astronomical Society of the Pacific), p. 375.

Wilkinson, D.T. 1988, in *IAU Symp. 130, Large Scale Structures in the Universe*, eds. J. Audouze, M.C. Pelletan and A. Szalay (Dordrecht: Kluwer), p. 7.

H.W. Duerbeck, R. Duemmler, H. Horstmann, H.-A. Ott, P. Schuecker, W.C. Seitter, D. Teuber, and H.-J. Tucholke: Astronomisches Institut der Universität Münster, Wilhelm-Klemm-Str. 10, D-4400 Münster, F.R. Germany.