Jean-Claude FAUVET, F, Electronics Engineer, 31. 8. 1980
Robert CLOP, F, Mechanical Engineer, 31. 8. 1980
Wolfgang RICHTER, D, Head of Engineering Group, 31. 8. 1980
Gérard SCHMITT, F, Electronics Technician, 31. 8. 1980
Jacques OTTAVIANI, F, Laboratory Technician (Electronics), 30. 9. 1980
Michel DENNEFELD, F, Astronomer/Physicist, 30. 9. 1980
Maurice LE LUYER, F, Senior Optical Engineer, 30. 9. 1980
Françoise PATARD, F, Secretary, 30. 9. 1980
Renate VAN DOESBURG, D, Secretary, 30. 9. 1980
Paul DE VOS, NL, Mechanic, 31. 10. 1980

ASSOCIATES

ARRIVALS

Europe

Ian GLASS, EIR, 1. 10. 1980
Philippe VERON, F, 1. 10. 1980
Marie-Paule VERON, F, 1. 10. 1980

DEPARTURES

Europe

Piero SALINARI, I, 31. 8. 1980
Jacqueline BERGERON, F, 30. 9. 1980

FELLOWS

ARRIVALS

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Walter EICHENDORF, D, 1. 9. 1980
Uno VEISMANN, EW, 1. 10. 1980
Harald WALDTHAUSEN, USA, 1. 11. 1980
Hélène SOL, F, 1. 12. 1980
Joachim KRAUTTER, D, 1. 12. 1980

DEPARTURES

Europe

Guillermo TENORIO-TAGLE, MEX, 31. 8. 1980
Jeremy A. SELLWOOD, UK, 30. 9. 1980
Danielle-Marie ALLOIN, F, 14. 9. 1980
Daniel KUNTH, F, 30. 9. 1980
Hans R. DE RUITER, NL, 30. 9. 1980
Jean SURDEJ, B, 30. 9. 1980
Eduardus ZUIDERWIJK, NL, 30. 9. 1980

Optical and Radio Studies of Supernova Remnants in the Local Group Galaxy M33

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The discovery of the first supernova remnants in M33 was made on material from a medium-size telescope but the subsequent detailed investigation involved the use of some of the largest optical and radio astronomy facilities in the world. Eventually, a complete study of these objects will improve our understanding of the stellar population and of the interstellar medium of that galaxy.

1. The Optical Search

At the present time about 130 extended galactic nonthermal sources have been classified as remnants of supernova explosions. Of these, only 30 have an identified optical counterpart, which, depending on the environment of the supernova and the age of the remnant, may consist in a few, faint filaments or in a nearly complete shell. The discrepancy between radio and optical identifications is due to galactic absorption and quite naturally has led optical astronomers interested in the subject to look in nearby extragalactic systems, where absorption conditions may not be so extreme. In the early seventies Mathewson and Clark pioneered this type of work by searching in the Magellanic Clouds. They started from a list of non-thermal radio sources, noting that in the shock ionized gas which is responsible for the optical emission, the strength of the [SII] emission lines at $\lambda\lambda 6717-6731$ is about equal to that of $H\alpha$, whereas in radiatively ionized nebulae they are one order of magnitude fainter. This effect is now understood from models of shocked radiating and cooling gas where temperature stratification can give rise to emission from a wide range of ions of differing ionization potential.

By observing at the position of the radio sources in $H\alpha$ and [SII] light, Mathewson and Clark (*Ap. J.* **180**, 725, 1973) were able to identify 14 SNR on the basis of strong [SII] emission. In 1976 one of us, S. D., then working in the Asiago Observatory of the University of Padova in collaboration with Benvenuti and Sabbadin, started a similar search in the Local Group Sc galaxy M33 (Fig. 1). At the distance of 720 kpc, the Crab Nebula would appear stellar-like and an older remnant like IC443 measure a few arcseconds. High angular resolution was required to identify a shell structure when possible, to separate the remnants from nearby HII regions and to lower the background emission from the galaxy in order to observe faint features. For M33 there was no list of non-thermal radio sources to start with, but fortunately the angular extent of the galaxy is such that it can be covered with a reasonable number of plates. Additional attributes of M33 are the favourable orientation (close to face on), the high gas/mass ratio and the relatively large number of young, massive stars which eventually will explode as SN. The plates were obtained at the Cassegrain focus of the Ekar 1.82 m telescope (scale 12.5"/mm through Hα, [S II] and red continuum filters and a VARO image tube. The first set of plates centered on the main southern spiral arm were carefully compared and happily revealed three nebulae with the strong [S II] characteristic (*A&A* **63**, 63, 1978). One indeed appeared as a half completed shell

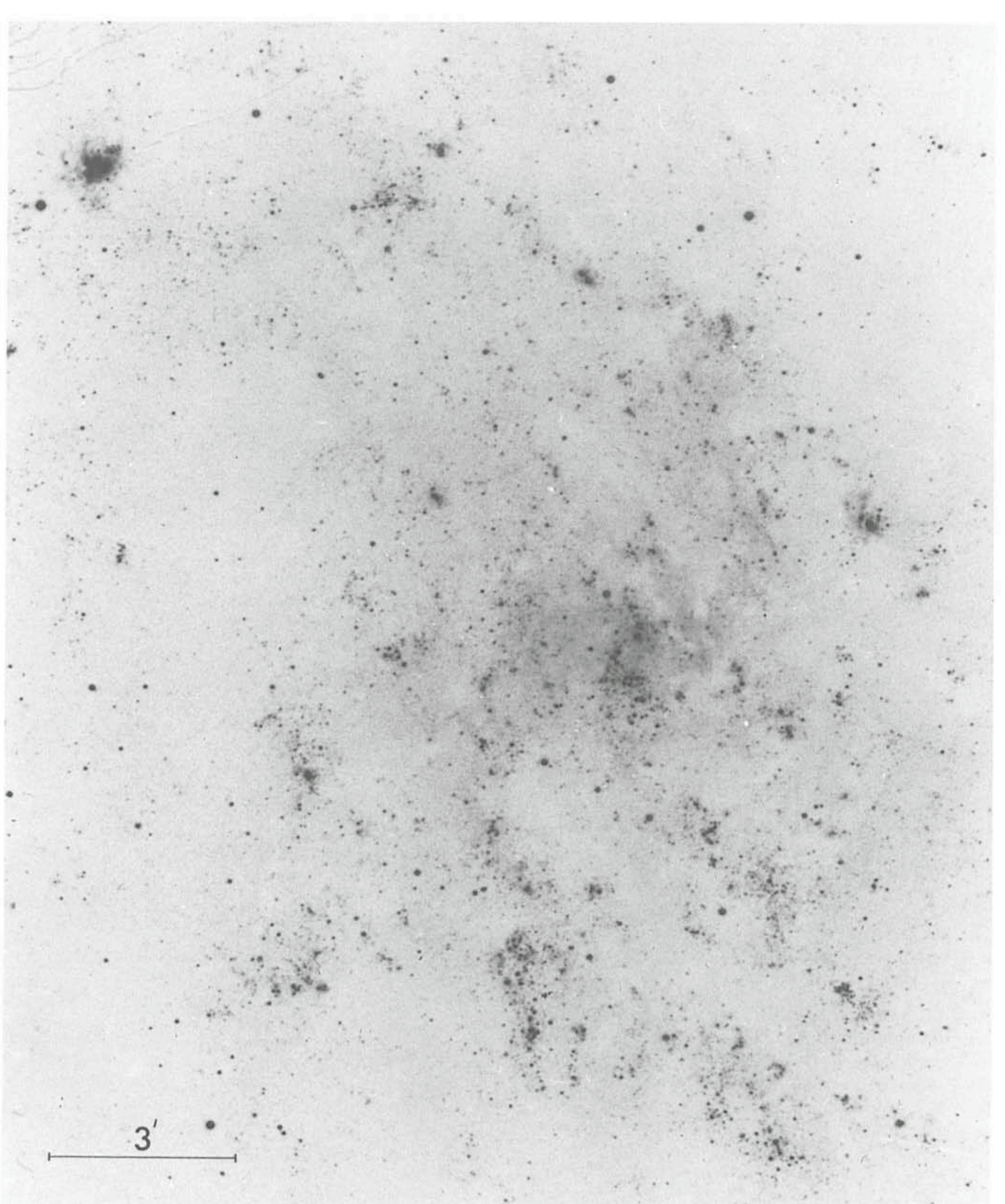

Fig. 1: *This ultraviolet photograph of the central part of M33 shows the spiral pattern as outlined by the OB associations. Asiago 1.82 m telescope, 103a-O plate + UG2 filter.*

probably caused by the interaction of the expanding shock with a nearby region of star formation (Fig. 2). The result was in a way expected, a natural follow-up of the Galactic and Magellanic Cloud work, but it was still rather exciting to find for the first time the place of a supernova explosion a thousand years after the event beyond the Magellanic Clouds.

Later on D'Odorico and Benvenuti joined Dopita, who had obtained observing time at the Palomar Schmidt on a similar programme to extend the survey to the whole galaxy. The Palomar plates complemented well the Asiago material because, with the wider field and fainter limiting surface brightness, they permitted the detection of large remnants in the periphery of the galaxy (*A&A Suppl. Ser.* **40**, 67, 1980). At present 20 SNR candidates are known in M33 with diameters from 6 (upper limit) to 60 parsecs.

2. The Optical Spectroscopy

The spectroscopic observations of the first 3 candidates in M33 were made with the UCL Image-Photon-Counting System attached to the RGO spectrograph at the Cassegrain focus of the 3.9 m Anglo-Australian Telescope in November 1977 by Danziger, Murdin, Clark and D'Odorico (*M.N.R.A.S.* **186**, 555, 1979). The system has several advantages for this type of work. There is the long slit mode allowing one to sample data from different regions of extended objects; there is the pulse-counting capability which allows one to make on-time assessments of the quality of the data particularly valuable for faint objects where accurate sky subtraction is essential; and there is the availability of a range of spectral resolutions which provide different types of spectral information. All of these capabilities proved useful as we shall see. At the AAT on the first night of the observations, as a result of the faintness of the objects and the large zenith distance ($>62^{\circ}$) at which the northern galaxy M33 had to be observed, there was a mood of skepticism about the possibility of the undertaking. Ten minutes into the first integration on object (SNR 1) the mood suddenly changed to one of elation as it was realized that the on-line [SII]/Hα ratio clearly indicated a small SNR on a section of the slit. (In fact a partial first draft of the *M.N.* paper was written that night while other observations were proceeding.)

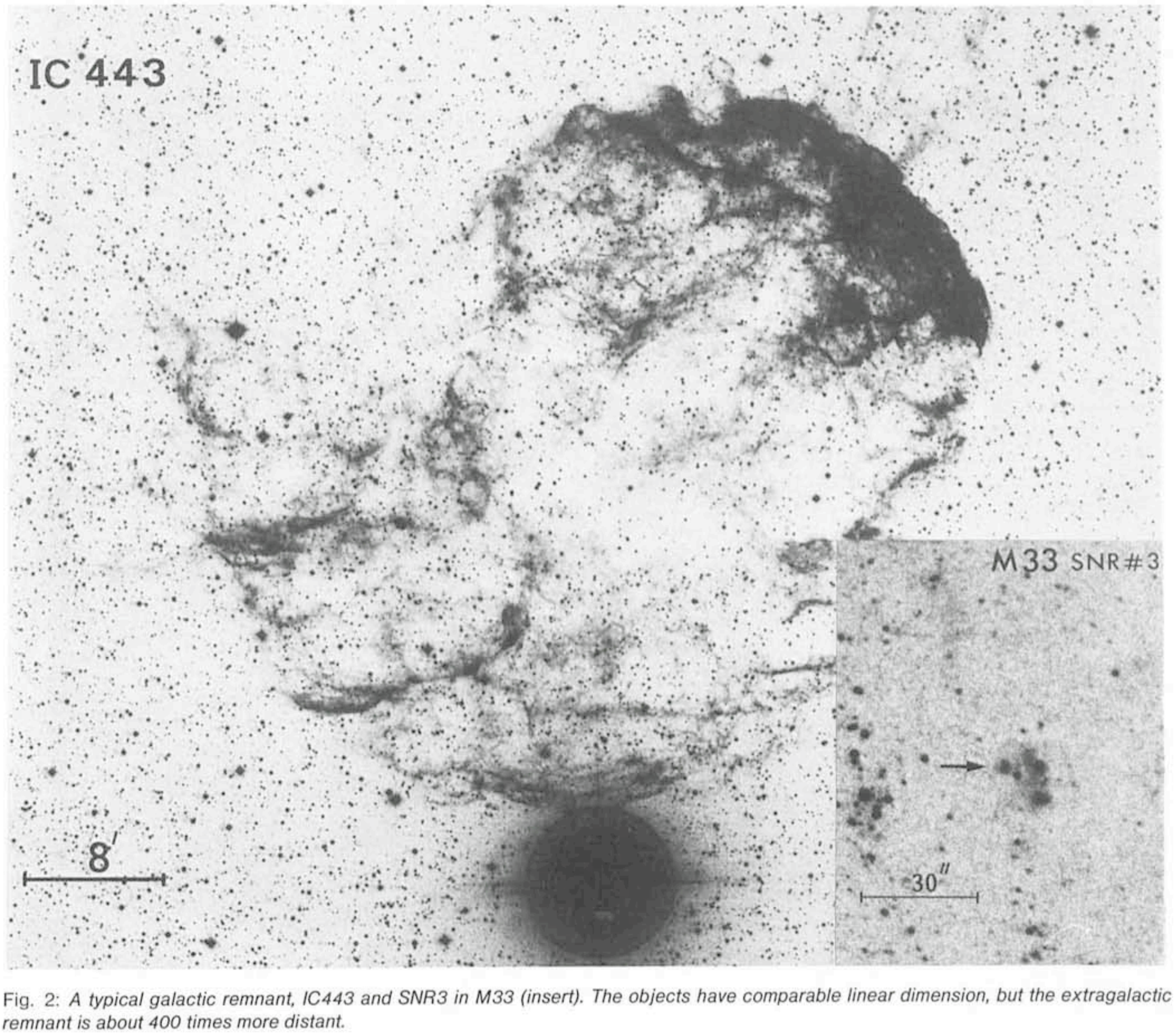

Fig. 2: *A typical galactic remnant, IC443 and SNR3 in M33 (insert). The objects have comparable linear dimension, but the extragalactic remnant is about 400 times more distant.*

A sample of a low-resolution spectrum of SNR2 is shown in Figure 3 where the great strength of the [SII] lines demonstrates the probability that this object is a supernova remnant. There are other pieces of evidence that suggest, but individually do not prove conclusively, that such objects are supernova remnants. Two of the objects have electron densities Ne $\sim 2 \times 10^3$ cm^{-3} (determined from [SII] doublet ratios), a value an order of magnitude higher than that observed in most HII regions.

The [OI] 6300 lines also tend to be stronger than observed in HII regions. Both of these effects are typical of supernova remnants in our Galaxy. A more compelling piece of information for SNR 1 is the presence of broad wings of low intensity (illustrated in Figure 4) on the profiles of the [OIII] 5007 emission line. This is the type of profile one might expect from a spherical shell of gas expanding outward from a central point. In the case of SNR 1 the velocity of expansion is > 375 km sec^{-1}, an order of magnitude higher than one ever observes in HII regions, but not uncommon in supernova remnants. This fairly high velocity and the small size of SNR 1, suggest that it is a relatively young object, not more than a few thousand years old.

The observations at the AAT with a long slit also demonstrated that these objects had a size greater than the seeing disk and had therefore an extent consistent with their being supernova remnants of young to intermediate age. One problem in this type of spectroscopy is the confusion of the SNR with nearby or intermixed HII regions. A high percentage of cases both in M33 and the Magellanic Clouds shows associated HII regions. This is one reason that care is required in using the spectra for interpretative purposes.

This spectroscopy allowed the above authors to discuss whether abundances obtained from these SNR spectra were consistent with abundances obtained from HII regions at similar positions by Smith (*Ap. J.* **199**, 591, 1975). No glaring discrepancies were found. A more extensive survey, detection and interpretation of SNR's in M33 have now been completed by Dopita, D'Odorico and Benvenuti (*Ap. J.* **236**, 628, 1980) using the Palomar 5 m telescope.

There have been occasional candidates from the direct observations which were not clear cut. It is reassuring to note that the spectroscopy and radio observations discussed below have been mutually supportive in helping to eliminate objects that are not SNR's.

3. The Radio Survey

In the initial Asiago Survey of the southern spiral arm of M33 the suggestion was made that several of the optical supernovae could be associated with radio sources. These sources had been found in a sensitive survey made in 1974 by Israel and van der Kruit (*A&A* **32**, p. 363) using the Westerbork Synthesis Radio Telescope (WSRT) at 21 cm. At the time of the Asiago Survey the radio continuum spectra and the positional agreement of the optical and radio objects was not known.

After the spectroscopic study at the AAT, we decided to extend the radio observations. These new observations are described in a paper in *Monthly Notices of the Royal Astronomical Society* (in press, 1980) by Goss, Ekers, Danziger and Israel. A new WSRT map at 21 cm has been made. The sensitivity is a factor of three improved in comparison to the 1974 map and the resolution is 25 × 49 arcsec. In addition we have used a 49 cm map

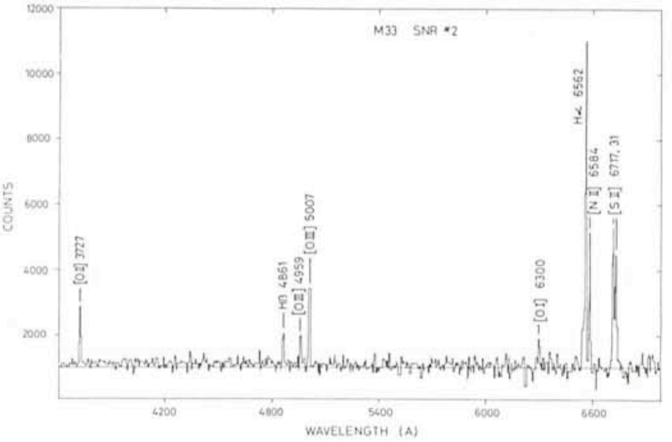

Fig. 3: *The λλ3500 – 7000 Å spectrum of SNR 2 in M33 obtained with the IPCS at the 3.9 m AAT. Spectral resolution 5 Å.*

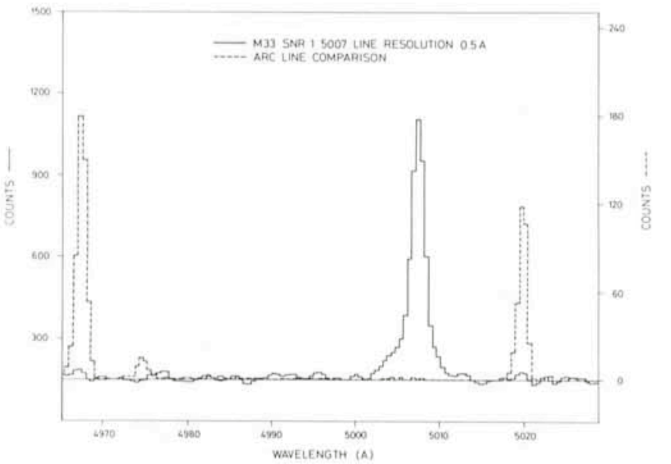

Fig. 4: *Velocity profiles of emission lines from SNR 1 and from the arc comparison. Broad wings in the SNR emission indicate a velocity dispersion larger than 375 km s^{-1}.*

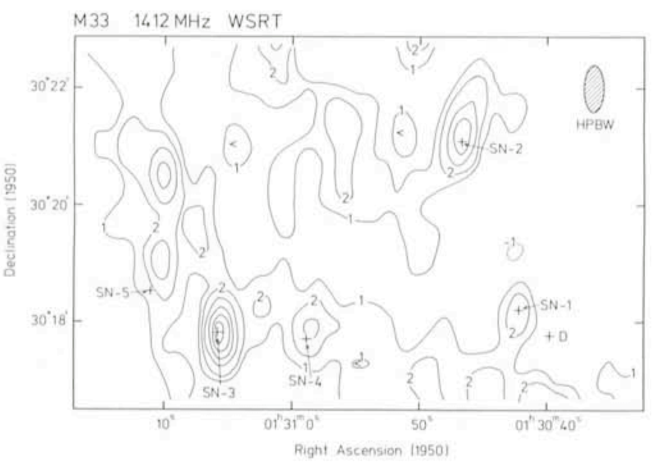

Fig. 5: *A 21 cm map of the southern spiral arm of M33 made with the Westerbork Synthesis Radio Telescope. The observing time was 2 × 12 hours, the beam width 25 × 49 arcsec and the r.m.s. noise 0.2 mJy per beam. One contour unit is 0.65 mJy per beam. The 5 SNR candidates from the Asiago survey are indicated: No. 1, 2 and 3 have been confirmed by the radio observations.*

made with the WSRT in 1975 in order to extend the radio spectra. The 21 cm map is shown in Figure 5; the five Asiago SNR candidates are shown. The SNR 1, 2 and 3 are the objects confirmed in the AAT study.

In 1978, we used the Very Large Array of the National Radio Astronomy Observatory in Socorro, New Mexico, to map SNR 1 and 2 at 6 cm. The goals were to determine the radio sizes with an angular resolution of 1.5 arcsec and to measure the flux densities at 6 cm.

The main results of the radio observations are:

(1) SNR 1, 2 and 3 have non-thermal radio spectra in the range 6 to 49 cm. The spectra are similar to galactic SNR.

(2) The radio positions agree precisely with the optical positions. There is little doubt of the correspondence of the two.

(3) Based on the measured angular sizes at 6 cm, the distance to M33 can be estimated. We assume the surface brightness (flux density/square of the angular size) diameter relationship for our Galaxy holds for M33. The determined distance is 860 $\pm$ 200 kpc. Although the error is large, the result is in good agreement with optically determined values.

We have also used the new 21 cm WSRT map to look for radio counterparts of the 20 new SNR candidates found at Palomar. In order to increase the reliability of the identifications, the optical positions have been measured to a precision of about 1 arcsec. Only two new positive identifications of weak radio sources and optical SNR can be made (two more are possible). It does appear that of the roughly 100 discrete radio sources in the WSRT map of M33 only very few can be unambiguously identified with optical SNR. The remainder of the radio sources are HII regions. Why is the rate of detections so low? This is simply a matter of sensitivity. Although we can detect a point source of 0.4 milli-Jansky throughout the disk of M33, this corresponds to a galactic SNR of $\sim$200 Jy at a distance of 1 kpc. There are very few galactic SNR of such intensity. Thus with presently available radio techniques we can only detect the strongest SNR in M33.

4. How Complete is the SNR Sample in M 33?

From the above discussion, it is fair to remark that in the case of M33 the optical method of identification has still an edge with respect to the radio surveys. This is also true for the 0.5-4.5 keV imaging survey of M33 obtained with the Einstein Observatory. Only nine sources were detected in the galaxy field and no coincidences were found with the optical candidates.

This is not unexpected because, at the detection limit of the instrument, a source equivalent to the Cygnus Loop at the distance of M33 would not have been detected and very young remnants (possibly one or two) with strong X-ray emission could not have yet developed a significant optical counterpart.

There are two main reasons of interest in the SNR counts in M33. We can use them to check the SN frequency in a Sc galaxy (this time looking at all SN exploded in a single galaxy during the last few thousand years instead of looking at several galaxies over a few years interval). Second, we can pinpoint the location of the SN explosions and try to associate them with the stellar populations.

At present, we have no way to say whether an observed remnant is due to a type I or type II supernova. At this point one may wonder about the completeness of the sample of 20 SNR selected on the basis of the [SII]/Hα criterion.

Two confusion effects may play a role. First there is the problem of the large shells of ionized gas which originate as a consequence of supersonic stellar winds. It has been suggested by Lasker that the large loops seen in the Large Magellanic Cloud may have this origin (1977, *Ap.J.* **212**, 390) and by mimicking the line intensities and radio emission of SNR, contaminate their sample at large diameters. Several circular HII regions are present in M33 but their Hα/[SII] ratios do not appear as low as in the SNR candidates neither do we observe an excess of SNR with large diameters.

A second effect which will make our sample incomplete is the presence in the galaxy of SNR which do not obey the [SII]/Hα criterion either by the absence of [SII] lines, like the faint filaments in Tycho and the stationary knots in Cas A, or by being oxygen-rich with little H, N and S to give rise to the red emission lines (like G292.0 + 1.8 as reported by Goss et al. *M.N.R.A.S.* **188**, 357, 1979). These characteristics however are peculiar to a few, probably young SNR and should have little effect on the global statistics.

Observations of Radio Galaxies

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It appears that only ellipticals become powerful radio galaxies. We believe this to be due to the depth of the gravitational potential well and the characteristic paucity of interstellar material in these galaxies. Aside from the particular interest of the nuclear activity associated with the radio galaxy phenomenon, these objects may, in two rather distinct ways, give us very useful information about the intergalactic medium in a range of different environments.

Firstly, there is growing evidence that the onset of nuclear activity and the subsequent generation of a powerful extended radio source may be triggered by a sudden increase in the gas content of the nuclear environment of an elliptical. This may be brought about by a close gravitational encounter with a neighbouring gas rich galaxy or even, perhaps, by the accretion of primordial intergalactic gas.

Secondly, once the extended radio source has formed, characteristically with a double-lobed morphology, its detailed properties can tell us something about the intergalactic medium with which it is interacting. The high-resolution, high-sensitivity radio maps now being made with the aperture-synthesis telescope show a very clear connection between the galactic nuclei and these sometimes