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KINEMATICS OF SUPERNOVA REMNANTS IN THE MAGELLANIC CLOUDS

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RESUMEN

En este trabajo se discuten los resultados de varios estudios sobre los remanentes de supernova (RSNs) en las Nubes de Magallanes. Se estudia la relación entre los RSNs y otras nebulosas vecinas a éllos, a partir de observaciones tanto de las nebulosas como de las estrellas. Se muestra el campo de velocidades radiales de toda la Nube Menor de Magallanes. Se presenta un nuevo método de identificación de RSNs basado en su cinemática que puede ser muy útil en la identificación de nebulosas chocadas en galaxias externas. Se discute cómo el conocimiento global de las propiedades de esta clase de objetos en una galaxia (en este caso, la Nube Menor de Magallanes) permite conocer la fase evolutiva de estos objetos.

ABSTRACT

In this article are discussed the results of several studies of supernova remnants (SNRs) in the Magellanic Clouds. We study the relations of SNRs and their environment based on observations of both nebulae and stars. We show the entire radial velocity field of the Small Magellanic Cloud. We present a new method of identification of SNRs based on their kinematics that can be useful for identification of shocked nebulae in external galaxies. We discuss how a global knowledge of the properties of SNRs in the Small Magellanic Cloud allows us to infer the phase of evolution of these objects.

Key words: **ISM: INDIVIDUAL OBJECTS (M42) — ISM: SUPERNOVA REMNANTS — MAGELLANIC CLOUDS — TECHNIQUES: INTERFEROMETRIC**

1. INTRODUCTION

The study of supernova remnants (SNRs) in a galaxy is important because it provides information on the mechanisms of the supernova explosion as well as on the interstellar matter (ISM) in the host galaxy. Indeed, SNRs are one of the most important sources of energy and heavy elements supplied by the stars to the host galaxy.

On the other hand, the Magellanic Clouds (MCs) are the nearest galaxies. They are located in a region of the sky with low interstellar absorption, they have large angular dimensions and they have properties different from those of our own Galaxy. This makes the Clouds quite attractive to study their SNRs and to compare with the more detailed studies of galactic SNRs.

We have approached the problem in two ways:

- Study of the detailed kinematics of a single SNR and,

- Study of the global aspects on the kinematics of the class of SNRs in the MCs.

Both approaches make use of optical observations with scanning Fabry-Perot interferometers (SFPIs). The results are radial velocities, mainly at Hα, with sampling resolutions of 5 and 15 km s^{-1} and photometric surface brightnesses of the velocity components up to 1.1 10^{-15} erg cm^{-2} s^{-1} sr^{-1}. The high spatial resolution observations, suitable for detailed studies of the kinematics of selected SNRs were made with the CIGALE equipment (Boulesteix et al. 1983) attached to the 1.52 m telescope of ESO which provides an angular resolution of 2.6 ″/px and an angular field of 7′. For the global studies we have made observations with the Hα SURVEY equipment, also installed at ESO (Amram et al. 1991, Le Coarer et al. 1992) which have modest angular resolutions of 9 ″/px but a wide field of 38′, sufficient to map the entire galaxies. Both data are complementary: in the first case we have the detailed velocity field of the SNR which allows us to know the particularities of its complicated kinematics; in the second case we have a global view of all the SNRs in a galaxy. High spatial resolution observations with the CIGALE equipment have been performed for several SNRs in the Large Magellanic Cloud (LMC) while the Hα SURVEY observations have been completed allowing us to have kinematic information on all (but one) of the SNRs in the Small Magellanic Cloud (SMC) and of their nebular environment.

2. SNRs IN THE LMC

2.1. The SNR N186D and the Nature of the Bubble N186E

The complex N186 is a 12′ diameter nebula composed of SNR N186D and a secondary bubble N186E. The SNR N186D has been identified as such due to its nonthermal radio emission, the high [SII]/Hα line-ratio and the detection of an associated extended source of soft X-rays. The complex N186 is located in a region of the LMC where several HI slabs at different velocities have been detected (Meaburn et al. 1984). The kinematics of both nebulosities show that they are located in the same HI slab because they have systemic velocities of 235 km s^{-1} coincident with the velocity of the more important HI slab in that direction. Thus, their proximity is real and not only due to a projection effect. In this situation we expect an interaction between these nebulae which is found in the kinematical data. Indeed, the velocity field of N186D is highly asymmetric: the red shifted emission is separated in location from the blue shifted one and those emissions have different morphologies. The red shifted material has a morphology similar to the [OIII] image whereas the blue shifted material resembles that of the [SII] emission (Laval et al. 1989).

We derived an expansion velocity of 90 km s^{-1} for the NE zone while the zone of interaction with N186E (at the SE) expands only at 50 km s^{-1}. The estimated value of the pre-shock density is 2.8 cm^{-3} and the energy deposited by the SN explosion in the moving gas is 2 10^{50} erg or 10^{51} erg, depending on the phase of evolution of this SNR (adiabatic or radiative, respectively).

Another interesting point is the nature of the second nebula: N186E. The faint components found in its velocity field have a pattern compatible with an expansion from a center which does not coincide with the geometrical center of the nebula and where no apparent early-type star is found. Thus, we concluded that this nebula could be a fossil SNR with a non-thermal radio surface brightness below the limits of sensitivity of current radio surveys (given its large diameter) or it could be an example of an off-centered supernova explosion in an already formed bubble (Rosado et al. 1990). In any case, there is further evidence that a SN explosion could be responsible for the kinematic field of this bubble: the presence of an extended X-ray source at the position of the presumed center of splittings. Figure 1, kindly lent by Dr. Y.H. Chu (1990), shows this X-ray source which has a smaller diameter than the optical one (but it could be a sensitivity effect) and luminosity in the IPC band of 7 10^{34} erg s^{-1}, i.e., at least one order of magnitude higher than the X-ray emission of a wind-blown bubble. We must, therefore, be clear that the derivation of ages for SNRs inside of wind-blown cavities should be completely different from the ages derived by considering the evolution of the SNR in a homogeneous medium.

The above results show that there is an interaction between two SNRs, confirming the feasibility of the scenario of Cox & Smith (1974) for the formation of interstellar tunnels.

2.2. The Nebular Complex N120 and its SNR

Being interested in the study of the interactions between a SNR and its parental or coeval nebulae, we have studied the nebular complex N120 which is an association of several smaller nebulae of different origins (HII

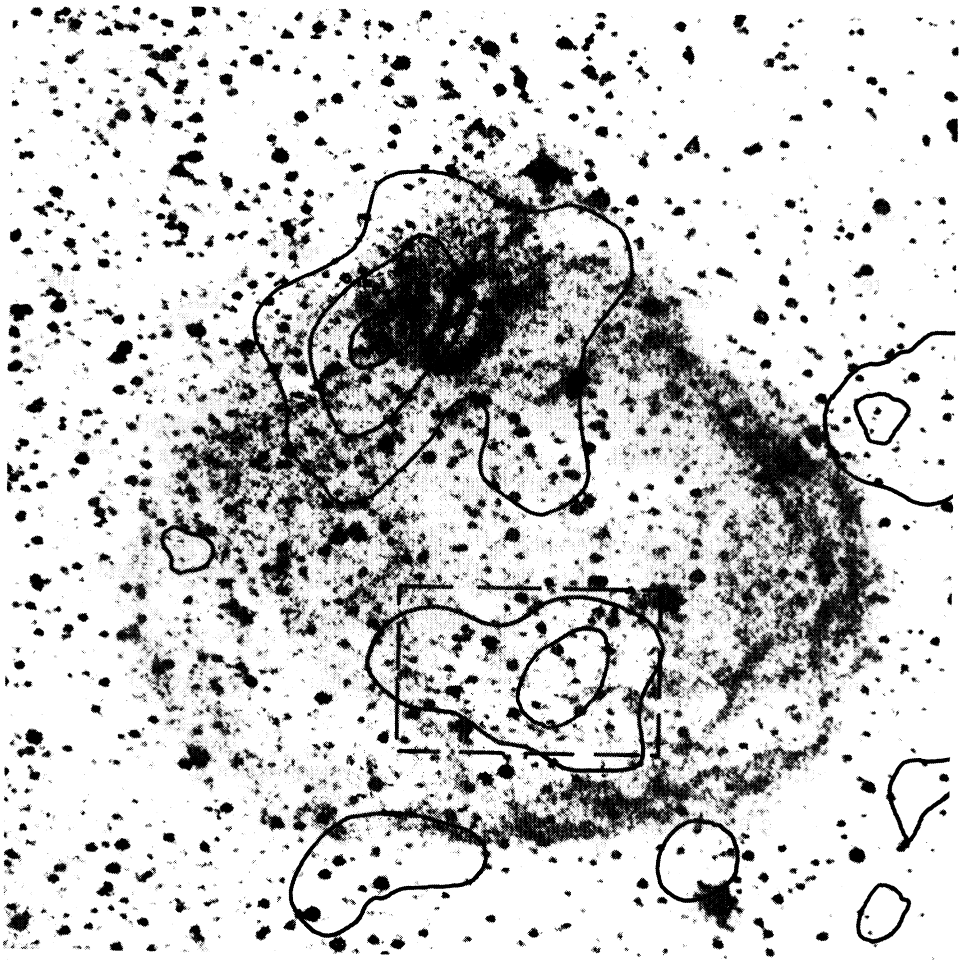

Fig. 1.— The nebular complex N186 in the LMC. North at the top and East at the left. The countour levels of the X-ray emission detected by the Einstein Satellite (solid lines) are superposed to the Hα photograph. The bright source (at the North) is SNR N186D. The X-ray source located inside the bubble N186E coincides with the zone of splittings of the FP profiles (broken rectangle).

regions, wind-blown bubbles, a SNR) forming a semicircular arc. This complex is located in one of the LMC spiral arms seen projected against the bar (Laval et al. 1992).

The kinematics of the SNR N120 show that the velocity profiles are highly contaminated by the emission of the nebular complex. The HII region profiles are sometimes broad and the systemic velocity of the SNR coincides with that of the HII region emission indicating a real association between the SNR and the nebular complex. We detect fainter components associated with the SNR emission whose velocity varies from 150 to 350 km s^{-1} causing splitting of the velocity profiles. However, as it has been observed in other SNRs (Chu & Kennicutt 1988), the widths of the components are also quite large (FWHM = 85-103 km s^{-1}) and they are correlated with the velocity of the component. The broadening of the velocity components could be due to induced shocks in denser cloudlets (McKee & Cowie 1975). These velocity widths suffer from the same geometrical effects than the radial velocities do. Furthermore, the shock velocity obtained from the difference between the highest values of the approaching and receding velocities coincide with that derived from the velocity widths (FWHM values).

The velocity field of this SNR illustrates how a detailed study with good spatial and spectral resolution is important to take into account the complexities of the kinematics of a SNR. We derived a value of the pre-shock density of the cloudlets of 8 cm^{-3}, an age of 7300 yr and an initial energy E_0= 5 10^{50} erg. The SNR would evolve in the Sedov phase (Rosado et al. 1993a).

In the cases mentioned above we find several common features:

- The radial velocity profiles of the SNR are always contaminated by bright emission from a HII region.

- The "contaminating" HII region is truly associated with the SNR.

3. SNRs IN THE SMC

These SNRs have been studied with the Hα SURVEY equipment mentioned before. We have performed a kinematic Hα survey covering the whole SMC (Le Coarer et al. 1993). Figure 2 shows the radial velocity field of the SMC obtained from these observations.

As a result, we have detected all but one of the SNRs already identified in this galaxy (Mathewson et al. 1983, 1984). They are clearly recognized in the λ-maps obtained from the Fabry-Perot scanning, because they show emission even at very large velocity channels. Incidentally, there appear other nebula which show this property which is related with the existence of shocks in the ISM. Thus, the SFPI λ-maps are a powerful tool in the detection of shocked nebulae even in more intricate ambients (i.e., inside HII regions). This new kinematic identification method could be easily applied in the search of SNRs in more distant galaxies (Rosado et al. 1993b). Figure 3 illustrates this method. As a first step in the work, we have obtained "integrated velocity profiles" (integrated over the whole dimensions of each SNR). These are interesting because this type of profile is what one should obtain for SNRs in more distant galaxies. The main characteristics of these profiles are:

-They are always complex indicating the presence of several components at high velocities (this is different from the simple velocity profiles of the HII regions (Le Coarer et al. 1993)).

- All of them are contaminated by the emission of brighter HII regions.

There is some controversy of what quantity measures the best the shock velocity (Rosado 1986, Chu & Kennicutt 1988):

1) The difference between the most negative and the most positive velocities, $(V_{+} - V_{-})$

2) The difference between the most negative (or positive) velocity and the velocity of an associated HII region, $(V_{+/-} - V_{HII})$

3) The FWHM of broadened profiles

4) The FWZI (full width at zero intensity) of broadened profiles

1) has the difficulty of always detecting both the approaching and the receding velocity components, 2) has the implicit assumption of the real association with the HII region, 3) requires a good subtraction of the HII emission, and 4) requires a very good signal to noise ratio. By far, the easiest quantity to obtain from the integrated profiles is 2), thus it is important to discriminate if the HII regions are physicaly associated with the SNR or if they are only foreground or background nebulae. This would require the study of the detailed velocity field as has been done for the SNRs in the LMC (Sect. 2). Given the fact that our detailed studies on other SNRs have shown a real association, we can take as a hypothesis that the association SNR-HII region is real. Thus, we can extract the following information:

a) the shock velocities can be obtained from the difference between the most negative or most positive SNR velocity and that of the associated HII region

b) the systemic velocity of the SNR should be that of the HII region

The shock velocities, V_s, obtained this way show a shallow correlation with the SNR diameter, D, of the form:

$$V_s = \text{constant } D^{(-0.44\pm0.23)}$$

This is the same type of dependence found years ago for SNRs in the LMC (Rosado 1986). The exponent of this correlation is incompatible with the idea of SNRs in the Sedov or in the radiative phase of evolution. It could imply, marginally, that the SNRs are in the free-expansion phase (quite strange because most of them have large diameters), but, curiously, it is the same type of dependence that wind-blown bubbles have (Weaver

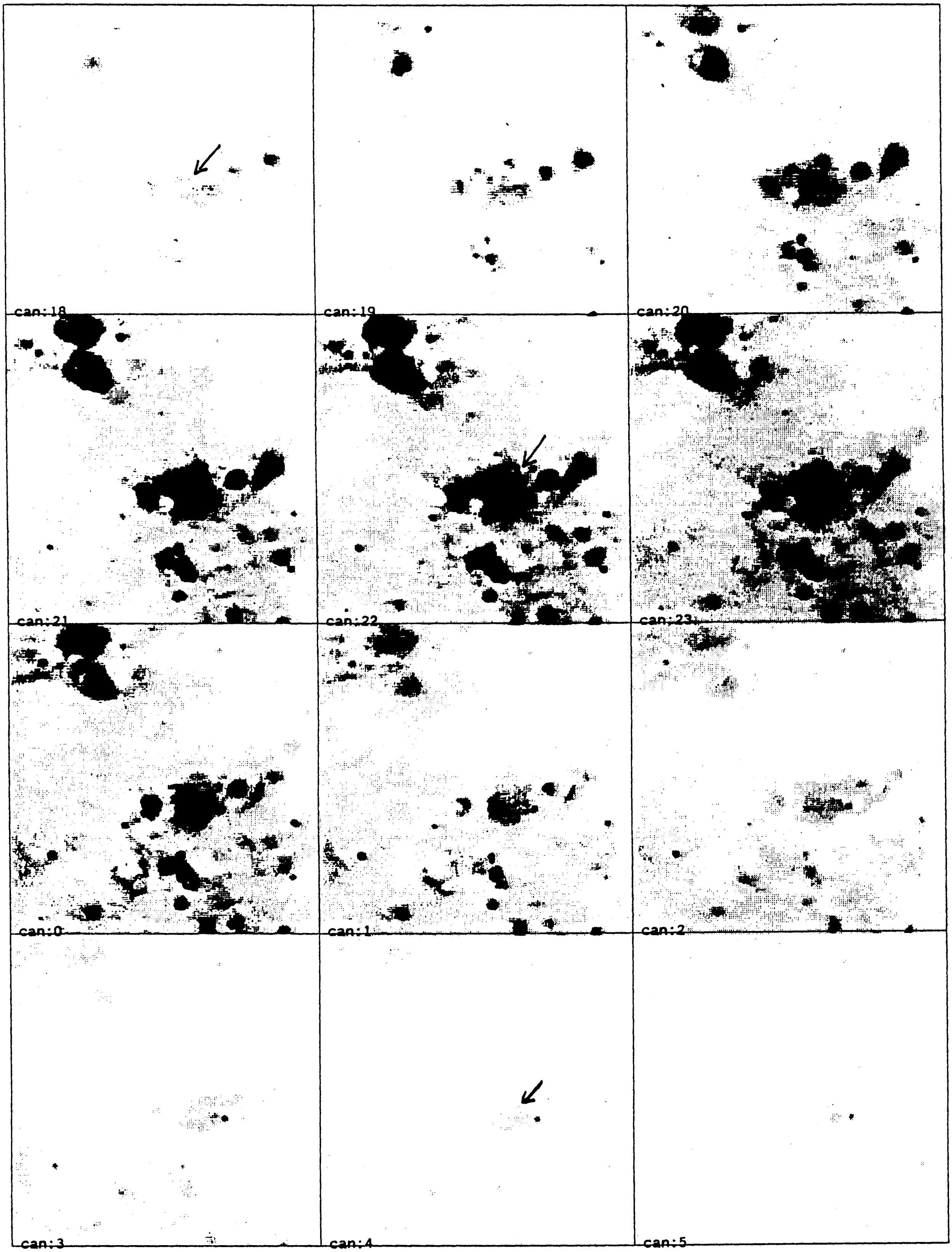

Fig. 3.— Fabry-Perot λ-maps of the field of the SNR 0045-734 is located (marked by an arrow). The difference in velocities between consecutive channels is 16 km s^{-1}.

et al. 1977). In this scenario, SN explosions in the SMC could have occurred inside the shells blown by the winds of the SN progenitor or other early-type stars.

On the other hand, recent studies (Martin et al. 1989) show that the SMC has a complicated velocity structure reflected in the detection of four complexes of gas and stars at different velocities (VL, L, H, and VH) and perhaps at different depths along the line of sight (the VL complex would be the nearest and the VH complex would be the farthest). Thus, the systemic velocities of the SNRs allow us to locate them in depth inside the SMC. Our preliminary results show that most of the SNRs in the SMC are more or less equaly distributed in the L and the H components. Since there is no clear attenuation of the optical and X-ray surface brightness of SNRs located in the H component (as compared with those located in the L component), we infer that the depth of the SMC (a matter of controversy) should not be large.

We note however that these implications are based on the hypothesis of a real SNR-HII region association which must be confirmed from detailed studies.

4. ACKNOWLEDGMENTS

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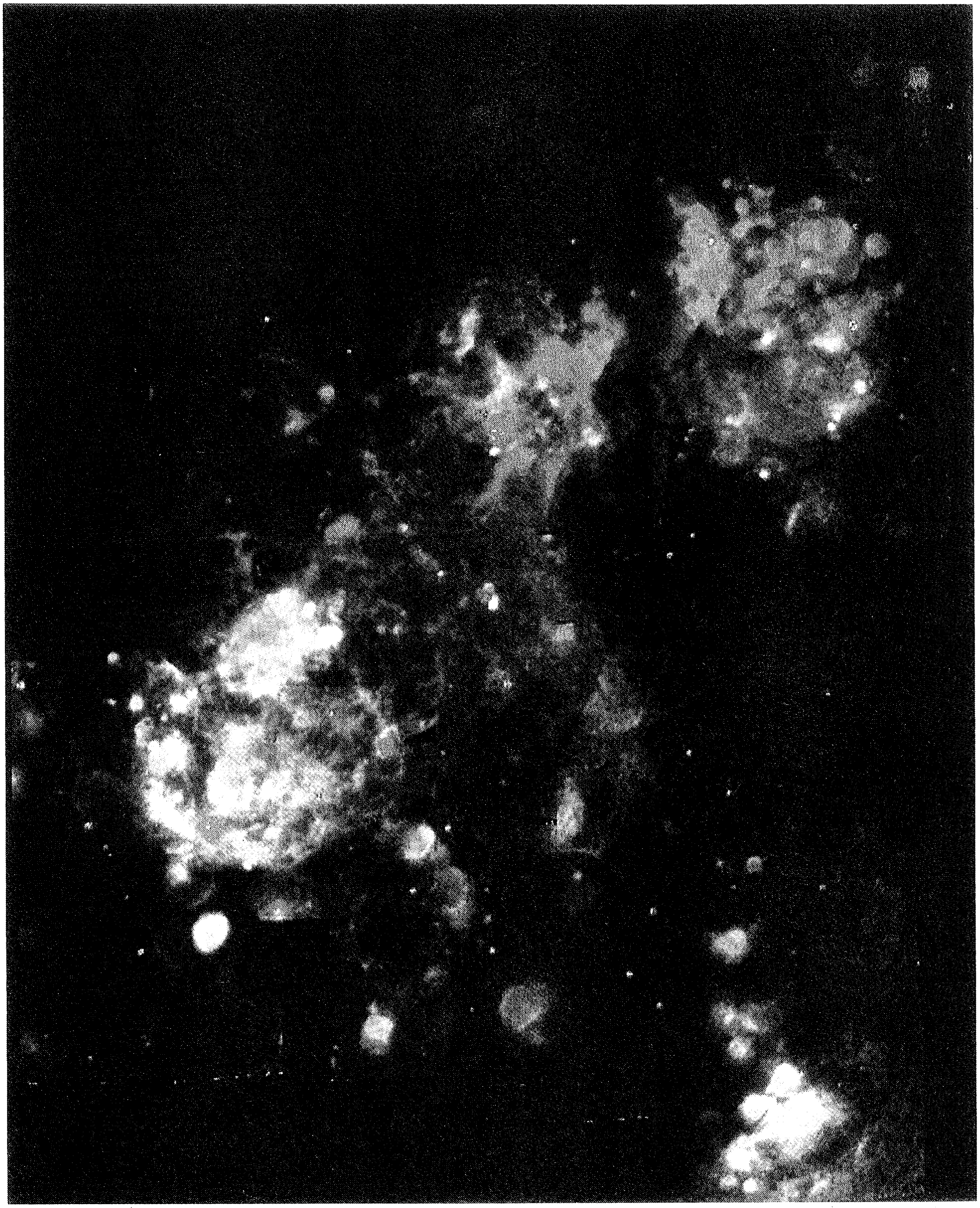

Fig. 2.— Velocity field of the SMC. Velocities are coded by different colors: dark blue=110 km s^{-1}, light blue=140 km s^{-1}, green=155 km s^{-1}, yellow=170 km s^{-1}, red=190 km s^{-1}, and white=205 km s^{-1}. The intensity of the color represents the brightness of the HII region.

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