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ON THE ORIGIN OF KEPLER'S SUPERNOVA REMNANT

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ABSTRACT

This paper presents a scenario for Kepler's supernova remnant whereby its emission is mostly due to the interaction of the blast wave with dense circumstellar matter, whose distribution is in turn determined by the interaction with a diffuse interstellar medium. The kind of observed asymmetry is easily explained if Kepler's supernova progenitor was a runaway object, subject to strong mass loss. Because of its velocity with respect to the interstellar medium, the outflow was deflected, resembling the situation of a comet. High-density clumps condensed near the front side, where matter was stagnating, and are dominating the optical emission at present. A mass loss with $\dot{M}w \sim 5 \times 10^{-4}$ ($M_\odot$ yr^{-1}) (km s^{-1}) is estimated for the progenitor; if the remnant is presently in Sedov phase, the wind parameters can be separated as $\dot{M} \sim 5 \times 10^{-5}$ $M_\odot$ yr^{-1} and $w \sim 10$ km s^{-1}. The runaway nature of the progenitor is discussed, and similarities with known runaway objects are presented. Specifically, binary Wolf-Rayet stars, P Cygni type stars, and some binary pulsars could belong to the same evolutionary track, leading to Kepler's supernova remnant.

Subject headings: nebulae: individual (Kepler's supernova remnant) — nebulae: supernova remnants — stars: winds

I. INTRODUCTION

Kepler's supernova remnant (SNR) has been commonly thought to be a Population II object. Its supernova (SN) light curve was consistent with a Type I event (Baade 1943); therefore a low-mass progenitor has been suggested. This hypothesis seemed to agree with its large distance from the Galactic plane. However, unlike other Type I remnants, Kepler's SNR shows evidence for dense circumstellar matter. The aim of this paper is to investigate the actual nature of Kepler's SNR and to derive several constraints on its progenitor.

Van den Bergh and Kamper (1977, hereafter VDBK) studied the velocity pattern of optical knots present in Kepler's SNR. Transverse astrometric or radial spectroscopic velocities have been measured for various knots. They do not seem to participate in the expansion of the remnant; a lower limit to their expansion age is $\sim 2 \times 10^4$ yr, while Kepler's SNR exploded only 380 yr ago. Therefore this matter is unlikely to have been ejected at the time of the SN event.

VDBK argued that the optical knots are composed of circumstellar matter. In fact, the small [S II]6717/6730 line ratios measured imply densities of nearly 10^3 cm^{-3} in the knots (van den Bergh, Marscher, and Terzian 1973; Dennefeld 1982; Leibowitz and Danziger 1983); such condensations would be very unusual for interstellar medium at the distance of many hundred parsecs from the Galactic plane, as in the case of Kepler's SNR.

Furthermore, models for the X-ray emission (White and Long 1983; Hughes and Helfand 1985) require a density of at least a few particles per cubic centimeter, while the local interstellar density should be less than $10^{-2.5}$ cm^{-3} (McKee and Ostriker 1977). VDBK suggested, as a further check on the circumstellar origin of the shocked medium, to look at the nitrogen abundances; Dennefeld (1982) measured in fact an overabundance of about a factor 4.

In spite of these strong clues there is the tendency to model this remnant as resulting from an explosion in the interstellar medium (White and Long 1983; Hughes and Helfand 1985). Two arguments are used to reject the idea of a circumstellar origin for the surrounding gas: the difficulty in reproducing the sharp northern limb, present in X-ray images, by using an original r^{-2} density profile, and the limitations on winds from low-mass, Population II stars, which are commonly taken as typical Type I SN progenitors. But in § III it will be shown that these arguments are not valid for Kepler's SNR; the northern limb will be explained by deviations from the r^{-2} density profile, due to the formation of a bow shock on that side. Furthermore, clues in favor of a high-mass progenitor will be presented.

In § V the problem of Kepler's SNR distance will be also discussed; an independent method, based on the model presented in this paper, allows one to estimate the remnant distance as $D_0 = 4.5$ kpc. This value will be used hereafter. Nonetheless, the explicit dependence on the distance will be retained in most of the formulae; for this purpose the symbol D will be used, for the distance scaled with D_0. Since Kepler's SNR Galactic latitude is 6°.8, its distance from the Galactic plane is $z_0 = 533D$ pc, while its angular diameter (200″) can be translated into a linear radius $R_0 = 2.18D$ pc.

The plan of this paper is the following: in § II a bow shock model for Kepler's SNR is presented, and the motion of the progenitor star with respect to the interstellar medium is evaluated; in § III the wind of the progenitor is studied, and its parameters are derived; in § IV physical conditions inside knots are investigated; in § V an independent estimate of the SNR distance is obtained, by comparison of the knots' pattern with the model presented in the paper; in § VI an analysis of candidate progenitors for objects like Kepler's SNR is attempted; § VII summarizes.

II. A STELLAR COMET

In the first part of this section some preliminary arguments are given, suggesting that the circumstellar density pattern around Kepler's SN progenitor is due to the interaction of the stellar wind with the interstellar medium. A model is introduced, in which a mass-losing star, moving with high peculiar velocity, creates a bow shock; the knots now emitting in optical have formed in this bow shock. Then, the peculiar velocity of the progenitor is estimated, on the basis of measured knot velocities.

The structure of Kepler's SNR is very asymmetric both in radio (Gull 1975; Matsui *et al.* 1984) and in X-ray (White and Long 1983; Matsui *et al.* 1984); the northern limb is in fact much brighter than the rest of the remnant. Moreover, all the optical knots lying at the edge are located in the northern sector (D'Odorico *et al.* 1986). Such a pattern can be ascribed to a density excess in that direction.

As already pointed out, at such a large z the interstellar medium should be very tenuous; moreover, its density should not vary on a scale of only a few parsecs. On the other hand, a stellar wind would hardly produce, by itself, the observed asymmetry. Even an anisotropic wind is expected to be centrally symmetric—with a density excess either at the equator or at the poles—for a single star, or an excess either on the orbital plane or orthogonally to it, for mass loss from a close binary system.

However, a pattern such as that observed can be reproduced when a mass-losing star is moving at high velocity; the wind interacts with the interstellar medium, forming a bow shock, where matter stagnates and gets denser. The flow pattern of the wind resembles, on a stellar scale, that in a normal comet. The problem of the interaction of two supersonic flows, one linear and the other radial, has been studied in comets (see e.g., Houpis and Mendis 1980). The main difference with comets is that there the flow is adiabatic, while here the shocked matter is likely to radiate most of its energy; Huang and Weigert (1982) presented a bow shock solution specific for this problem.

Huang and Weigert approximate the bow shock as a thin layer, dividing the space in two regions: an inner one, where the wind is expanding with constant velocity, and an outer one, where the interstellar medium is flowing linearly (in the stellar reference frame). Since these flows are supersonic, they interact only inside the bow shock; a result is that the density distribution in the inner region is not affected by the interstellar flow, and follows the standard r^{-2} profile with spherical symmetry.

The circumstellar matter lying on the front side participates in the motion of the central object. If, as in the case of Kepler's SNR, the subsequent interaction with the blast wave does not produce appreciable acceleration, the velocity of the progenitor can be easily inferred by measuring the motions of the circumstellar knots.

VDBK found that proper motions of the knots are consistent with small random velocities added to a common translation. Its (heliocentric) radial component is $U_R = -222 \pm 13$ km s^{-1}, while the transverse components in right ascension and declination are, respectively, $\mu_\alpha \cos\delta = -0''.0041 \pm 0''.0019$ yr^{-1} and $\mu_\delta = 0''.0109 \pm 0''.0018$ yr^{-1}. VDBK then applied corrections for Galactic rotation, assuming that Kepler's SNR is located in the nuclear bulge of the Galaxy.

Figure 1 shows the astrometric and spectroscopic background velocities, due to Galactic rotation, in the direction of Kepler's SNR; they have been obtained by using the Galactic rotation curve given by Clemens (1985) for the model of Gunn, Knapp, and Tremaine (1979) and must be subtracted from the observed values to obtain the remnant peculiar velocity. Corrections are within the quoted errors, for distances less than nearly 7 kpc. Assuming a distance of 4.5 kpc for the remnant, $U_R = -229 \pm 13$ km s^{-1}, $\mu_\alpha \cos\delta = -0''.0034 \pm 0''.0019$ yr^{-1}, and $\mu_\delta = 0''.0110 \pm 0''.0018$ yr^{-1}.

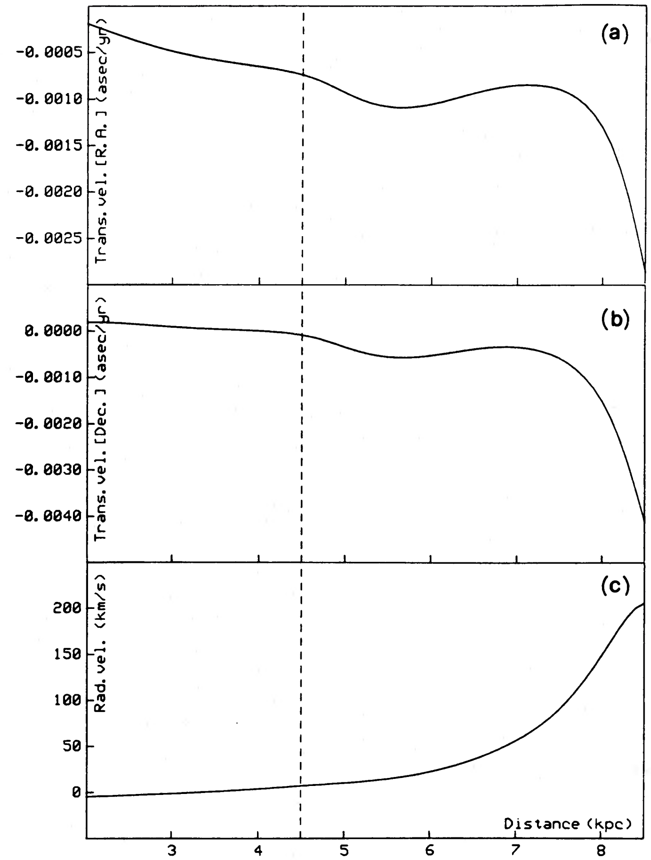

FIG. 1.—Background velocities, due to Galactic rotation, plotted vs. Kepler's SNR distance. Astrometric background velocities along (*a*) right ascension and (*b*) declination are plotted; (*c*) shows the trend of the background spectroscopic velocity. Dashed vertical line refers to the assumed distance of 4.5 kpc.

Angular velocities can be translated into linear motions; the transverse velocity is $U_T = 246 \pm 38D$ km s^{-1}, with a polar angle $\vartheta = -16° \pm 9°$. The total velocity of the progenitor relative to the interstellar medium is then $U = 336 \pm 30$ km s^{-1}. Its dependence on Kepler's SNR distance is rather complex; however, for distances close to that assumed, $U \propto D^{0.56}$.

Quoted errors refer only to uncertainties in measurements, under the assumption that the expansion of the knot pattern is negligible. However, VDBK found marginal evidence for expansion. Figure 2 shows the dependence of best fits for the transverse velocity on the amount of expansion. The velocity estimated above, that will be used in the following, assumes no expansion. Expansion velocities up to 200 km s^{-1} are in fact compatible with observations: but even in the extreme case the estimate of U would be only 14% smaller than that in absence of expansion.

It is worth wondering whether other unaccounted effects can decrease the reliability of the estimated velocity. If optical knots are expanding, spectroscopic velocity measurements can be biased in case of absorption on the redshifted side; on the other hand, astrometric variations of the emission peaks could reflect "phase velocities," rather than actual motions; moreover, a proper averaging requires each knot to be weighted with its own mass, which is unfortunately unknown. However, one is made more confident by the similarity between values of radial and transverse velocities (as expected on the basis of an *a priori* argument, averaging over random directions), although

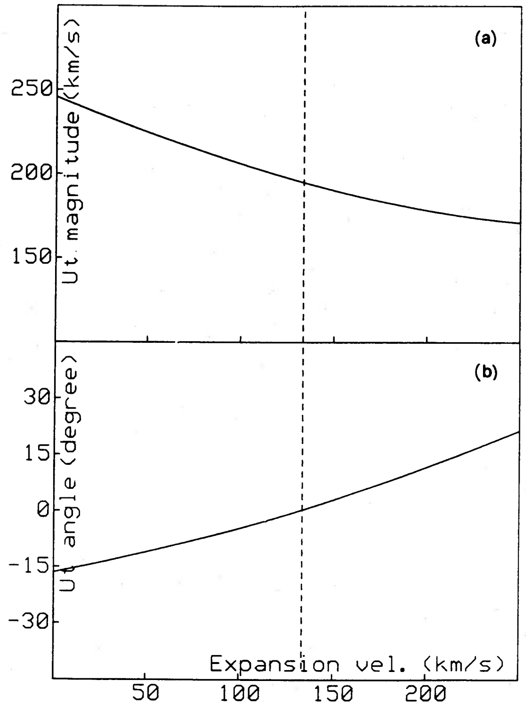

FIG. 2.—(*a*) Magnitude and (*b*) direction of the best fits for U_T vs. the assumed expansion velocity of the remnant. Dashed vertical line refers to the expansion which gives the best global fit.

obtained by completely different methods. In § V these values will be used with satisfactory results as constraints in a model for the observed knot pattern.

The derived translational kinetic energy of Kepler's SN progenitor is one order of magnitude larger than the potential energy due to its displacement from the Galactic plane. Therefore this star should have been a runaway object; assuming that it moved away from the Galactic plane with constant velocity, it must have left the plane only 3×10^6 yr ago; in the meanwhile it must have evolved into a SN: such a fast evolution is suggestive of a high-mass star. A further clue in favor of a rather massive and young progenitor, based on constraints on its mass loss, will be presented in the next section.

III. CONSTRAINTS ON THE OUTFLOW

In the frame of a bow shock model, the distance of the bow shock apex from the star, R_c, can be easily estimated as that at which the ram pressure of the wind is balanced by that of the interstellar medium: one derives

$$R_c = 94\sqrt{\dot{M}w}\, n_{2.5}^{-1/2} D^{-0.56} \text{ pc} ,$$

where $\dot{M}$ is given in $M_\odot$ yr^{-1} and w is in km s^{-1}; $n_{2.5}$ is the interstellar density scaled with $10^{-2.5}$ cm^{-3} (McKee and Ostriker 1977); R_c is inversely proportional to U, for which the value estimated in the previous section, as a function of the distance, has been used.

If the emission from the SNR reflects the density distribution of the matter reached by the blast wave, for shock radii smaller than R_c the remnant will look symmetric, while a conspicuous anisotropy will be observed only when the blast wave radius is comparable with, or slightly larger than R_c. One may then argue that, since Kepler's SNR looks now so asymmetric, the actual shock radius, R_0, is comparable with R_c. As expected, there is a good agreement between the direction of the transverse velocity and the mean direction of the brighter edge of the remnant, with respect to its center.

The stellar wind is then constrained to have $\dot{M}w = 5.4 \times 10^{-4} n_{2.5} D^{3.1}$ ($M_\odot$ yr^{-1}) (km s^{-1}). This result is based on the assumption of steady state; it holds only if the wind has gone on long enough to fill the space up to R_c. This requirement implies $\dot{M}/w \le 4.7 \times 10^{-7} M_t D^{-1}$ ($M_\odot$ yr^{-1})/(km s^{-1}), where M_t, in $M_\odot$, is the total mass expelled as a wind.

In the direction opposite to the progenitor motion the blast wave is still expanding in a medium with a r^{-2} density profile. A model including time-dependent ionization (Hughes and Helfand 1985) is required to make accurate predictions on the X-ray emission; nonetheless, Sedov (1959) theory allows one to see that the absence of a sharp limb, observed in the southern part of the remnant, is more consistent with an expansion in a medium with a r^{-2} density law than in a constant density medium. While in the latter case the shocked material is concentrated in a thin shell behind the shock front, in the former its density goes linearly with radius.

Sedov theory yields the relation $\dot{M}/w = 6Et^2/R_0^3$, where E is the energy of the SN explosion and t is the age of the SNR (380 yr). Therefore

$$\dot{M}/w = 4.5 \times 10^{-6} E_{51} D^{-3} \ (M_\odot \text{ yr}^{-1})/(\text{km s}^{-1}) ,$$

where E_{51} is the SN energy in units of 10^{51} ergs. It can be combined with the previous upper limit on $\dot{M}/w$, to derive the condition $M_t \ge 9.6 E_{51} D^{-2}$ $M_\odot$. If the assumptions of steady flow for the wind and that of Sedov phase for the blast wave are both correct, either the SN explosion was subenergetic, or the progenitor was originally rather massive and underwent a considerable mass loss, unless the actual distance of the remnant is grossly less than the value derived in § V. Such a massive progenitor is consistent with the kinematic age of 3×10^6 yr, previously determined.

The assumption of Sedov phase allows one to evaluate $\dot{M}$ and w separately, as

$$\dot{M} = 4.9 \times 10^{-5} n_{2.5}^{1/2} E_{51}^{1/2} D^{0.05} \ M_\odot \text{ yr}^{-1} ,$$

$$w = 11 n_{2.5}^{1/2} E_{51}^{-1/2} D^{3.05} \text{ km s}^{-1} .$$

The wind must have lasted for at least $2.0 \times 10^5 n_{2.5}^{-1/2} E_{51}^{1/2} D^{-2.05}$ yr.

IV. THE ORIGIN OF KEPLER'S SNR KNOTS

The internal pressure in the bow shock must balance the ram pressure on the incoming matter; taking for the stellar velocity U the value derived in § II (with its distance dependence), this criterion constrains

$$n_b T_b = 4.3 \times 10^4 n_{2.5} D^{1.1} \text{ cm}^{-3} \text{ K} ,$$

where n_b, T_b are density and temperature in the bow shock, respectively. While matter in the bow shock cools down, instabilities, mainly of thermal origin, are likely to intervene. This process will eventually form dense and cold knots; they will stay in pressure equilibrium with the surroundings ($n_K T_K = n_b T_b$, where n_K, T_K indicate knot density and temperature, respectively). This value of $n_K T_K$ refers to the time at which knots have been formed; it will change in case of further variations of the stellar wind, to maintain the pressure equilibrium, and, obviously, it will strongly increase when knots will be reached by the blast wave. The value of $n_K T_K \approx 10^{-7}$ cm^{-3} K, measured in Kepler's SNR optical knots (Leibowitz and Danziger 1983), is not at all in conflict with the value given above, since we see in optical only those knots that are already interacting with the blast wave.

From the absence of conspicuous expansion of the knot pattern (less than 200 km s^{-1}), one can argue that they were rather dense also before the arrival of the blast wave. A rough estimate is easily obtained: the blast wave is affected only locally by the presence of knots; then the knot acceleration can be approximately evaluated by using an unperturbed blast wave. A strong shock moving with velocity v_S in a homogeneous medium (with density ρ_0) deposits a momentum per unit volume equal to $3\rho_0 v_S/4$. A knot with density ρ_1 will be then accelerated up to $v = 3\rho_0/\rho_1 v_S/4$. With $v_S = 3740D$ km s^{-1} (for Sedov expansion) and $v_1 < 200$ km s^{-1}, the density contrast must be $\rho_1/\rho_0 > 19$. The wind parameters derived in the last section lead to $n_0 = 3$ cm^{-3} at the bow shock; then $n_1 > 57$ cm^{-3}. This lower limit refers to knots densities before the interaction with the blast wave. Leibowitz and Danziger (1983) estimate a preshock density greater than 10^3 cm^{-3} for knots; in this case the impact with the blast wave would communicate velocities less than 10 km s^{-1} to knots.

V. THE DISTANCE OF KEPLER'S SNR

The distance of Kepler's SNR is an important parameter for models. Unfortunately it is poorly known: recent estimates range from 3 to 9 kpc. In the former part of this section earlier attempts to measure it will be briefly reviewed; then an alternative method will be presented, based on the bow shock model.

Most of distance measurements make use of the observed magnitude of the SN, as derived from historical records. The conversion into standard visual magnitudes is, however, not straightforward, and values given by different authors are spread over more than a magnitude ($m_V = -2.4 \pm 0.25$, Baade 1943; $m_V = 3.0 \pm 0.3$, Clark and Stephenson 1977; $m_V = -3.5$, Pskovskii 1978; $m_V = -2.5$; Clark and Stephenson 1982). In the following I shall use $m_V = -3.0 \pm 0.5$.

Many authors used the assumption that Kepler's SN was a classical Type I SN; these objects are known to be standard candles ($M_V = -19.7$, according to Tammann 1982; however, an alternative estimate 1.3 mag fainter is presented by de Vaucouleurs 1985); therefore, measuring the extinction in the direction of Kepler's SN, its distance could be easily obtained. On the basis of reddening in field stars, VDBK found a visual absorption $A_V = 2.2 \pm 0.7$; while, on the basis of the Balmer decrement in the emission from optical knots, Danziger and Goss (1980) derived $A_V = 3.5 \pm 0.2$ (see also Dennefeld 1982). However, since the Balmer decrement varies from knot to knot (Leibowitz and Danziger 1983), leading to variations of more than 2 mag in A_V over a scale of a few arcsec, it is more suggestive of internal absorption, or absorption very close to some emitting knots, rather than of interstellar extinction. Thus, I will use hereafter the VDBK estimate.

A distance estimate based on the Kepler's SNR X-ray flux was attempted by Becker *et al.* (1980); by comparison with Tycho's SNR, they obtain $D > 5$ kpc. Radio Σ–D relationships including the effect of the distance from the Galactic plane have also been used. According to Caswell and Lerche (1979) $D = 5$ kpc, while according to Milne (1979) $D = 3$ kpc. However, Caswell and Lerche reported anomalies from the general Σ–D trend for young SNRs.

There is, however, a completely different way to derive the distance of this remnant, if one relies on the bow shock model. The bow shock is approximated as a thin, almost paraboloidal layer; inside this surface, density is spherically symmetric, and the blast wave will then propagate keeping a spherical shape. Optical knots, if they actually are condensations belonging to the bow shock, triggered by the arrival of the blast wave, must be located at the intersection of these two surfaces, namely on an annulus.

The projection of this annulus is an ellipse; its axis ratio depends on the tilt angle of the bow shock axis on the sky plane, which in turn depends on the direction of the star motion. The axis ratio B/A is $|U_R|/(U_R^2 + U_T^2)^{1/2}$. While the heliocentric radial velocity can be measured directly ($U_R = -229 \pm 13$ km s^{-1}), the transverse velocity, based on astrometric measurements, depends linearly on the distance ($U_T = 54.7 \pm 8.4 D_{\rm kpc}$ km s^{-1}). Then, the distance is derived in terms of the axis ratio,

$$D_{\rm kpc} = (4.2 \pm 0.6)\sqrt{A^2/B^2 - 1}\ {\rm kpc}\ .$$

The fit of an ellipse to the knot pattern would hardly be convincing, unless one can *a priori* constrain some of the free parameters (originally 5). In fact, three of them can be deduced from the observations: the direction of the transverse velocity, the position of the SNR center, and the radius of the remnant can be used to fix the orientation of the ellipse, to constrain its center on a line, and, using the model of Huang and Weigert (1982), to relate the size of the ellipse with its displacement from the center of the remnant.

The physical meaning of the two remaining parameters is the following: as already shown, the axis ratio is related to the distance of the remnant; the size of the ellipse is related to the actual radius of the blast wave (R_0), in units of the bow shock size (R_c). If the blast wave expands as T^α ($\alpha = 1$ for linear expansion; $\alpha = \frac{2}{3}$ for Sedov expansion in circumstellar matter; see § III), the time elapsed between the beginning of the interaction of the blast wave with the bow shock and the present time is

$$\Delta t = t[1 - (R_c/R_0)^{1/\alpha}]\ .$$

Figure 3 shows an overlay of the best fitted ellipse to a recent image of the knot pattern (D'Odorico *et al.* 1986): since the ellipse is expanding, it has been fitted to the outermost part of the emitting regions, that have probably been reached more recently by the blast wave. No reasonable automatic algorithm has been found for the fitting; then it has been done manually, by direct comparison of the image with various models. The derived distance is $D = 4.5 \pm 1.0$ kpc, where the estimated error takes into account both the uncertainties in the velocity determinations and those intrinsic in the fitting. The other derived parameter is $R_0/R_c = 1.22 \pm 0.03$; in the case of Sedov expansion, the interaction of the blast wave with the bow shock must have started 98 ± 10 yr ago. The dashed ellipses show the interaction region 20, 40, and 60 yr ago; one can compare them with some older photographs (e.g., with that of Baade 1943). Incidentally, such a comparison seems to rule out a linear expansion of the blast wave ($\alpha = 1$), since it requires an evolution of the ellipse size faster than actually observed.

Moreover, from the width of the edge, an average lifetime of 60 yr can be estimated for the optical knots. VDBK studied some newly born knots; they are in fact located on the outer side of the northern limb. In more recent images (D'Odorico *et al.* 1986) other new knots appear, all on the outer side. The model presented here leads to the following prediction: new knots appearing in the central region must be located to the south of those already existing. Unfortunately most of these

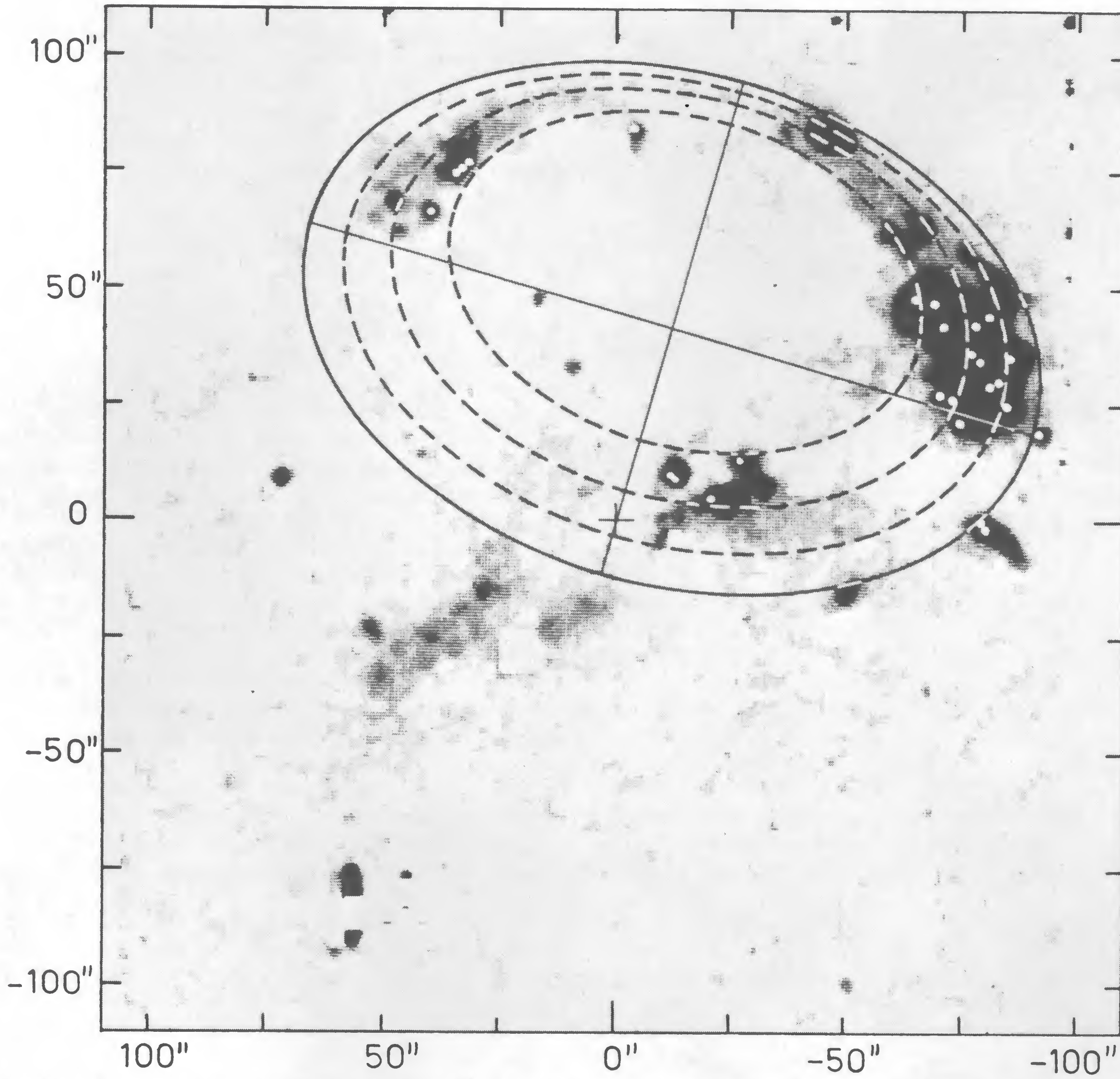

FIG. 3.—Overlay of the model to a Kepler's SNR image. Central cross indicates the center of the remnant (Matsui *et al.* 1984); on the axis the coordinates relative to that point are given. White dots indicate the optical knots listed by VDBK. Solid line ellipse represents the present location of the intersection between the bow shock and the blast wave; the two axes of the ellipse are also shown. Dashed line ellipses give the position of the intersection annulus 20, 40, and 60 yr ago (from outside inward).

knots are too faint for being easily recognized in old photographs.

Two assumptions are intrinsic to the method that I presented: negligible bow shock width, and the spherically symmetric stellar wind. The latter assumption is very crucial: anisotropies in the wind will distort the bow shock, also the blast wave would not be spherical. Some groups of fainter knots, whose positions are not consistent with the general trend (see Fig. 3, on the S-E side), could be possibly explained in this way.

The knowledge of the SNR distance allows one to derive also the absolute magnitude of the SN. With a visual magnitude $m_V = -3.0 \pm 0.5$, an interstellar extinction $A_V = 2.2 \pm 0.7$, and a distance modulus $m - M = 13.3 \pm 0.5$, the absolute magnitude is $M_V = -18.5 \pm 1.0$. According to Tammann (1982), this magnitude determination is less than expected for a classical Type I SN; it will be used in the next section, to infer the nature of Kepler's SN.

VI. DISCUSSION

To summarize the main results, Kepler's SN progenitor was a massive object ($\sim 10\ M_\odot$) subject to strong mass loss ($\sim 5 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$), with a low-velocity wind ($\sim 10\ \mathrm{km\ s}^{-1}$). It left the plane 3×10^6 yr ago, moving at a very high velocity ($\sim 340\ \mathrm{km\ s}^{-1}$); during this short time it evolved into a SN. This scenario is self-consistent; in the following I shall discuss its likelihood.

Since Kepler's SN exploded only 380 yr ago, one expects it to belong to a quite common type of SNe. The light curve derived from an analysis of the historical records looks like that of a typical Type I SN; however, the optical magnitude at maximum is fainter than expected for these objects. There are two possible ways to get over this inconsistency.

The first one is to assume that Kepler's SN has been a subluminous Type I SN (or Type Ib SN). Recently, Panagia (1985, 1986) and Panagia, Sramek, and Weiler (1986) recognized two classes of Type I SNe: the classical ones and the Type Ib, which are fainter by ~ 1 mag (Uomoto and Kirschner 1985). SNe belonging to the latter class have been detected only in spiral galaxies and are associated with H II regions or spiral arms; thus they are likely to originate from young, Population I stars.

Two such objects, namely SN 1983n and SN 1984l, have been discovered and extensively observed (Panagia 1985).

Radio emission (Sramek, Panagia, and Weiler 1984; Weiler *et al.* 1986) was also unexpectedly detected, turning on soon after the optical; such emission was interpreted as due to the interaction of the blast wave with a circumstellar medium (Sramek, Panagia, and Weiler 1984; Chevalier 1984). The radio light curves constrain $\dot{M}/w$ to be $\sim 5 \times 10^{-7}$ $(M_\odot\ \mathrm{yr}^{-1})/(\mathrm{km\ s}^{-1})$. This value is an order of magnitude less than that found in the case of Kepler's SNR; this discrepancy could be solved by assuming either that the wind parameters changed in the last stages preceding the SN, or that the energy released by the SN was considerably less than 10^{51} ergs.

Uomoto and Kirschner (1985) find that subluminous Type I SNe have a color index $B-V$ at least 0.8 mag larger than standard Type I SNe: if Kepler's SN was actually a Type Ib SN, it should then have appeared considerably redder than normal. The analysis done by Pskovskii (1978) leads in fact to an intrinsic reddening 0.63 mag more than the normal color. It seems significant that Pskovskii suggested a similarity with SN 1962l, an object that later has been recognized as a Type Ib SN. However, such a large value is not universally accepted: for instance, VDBK did not find any significant intrinsic reddening.

The other possibility is that Kepler's SN was a Type II SN linear (or Type IIL). Doggett and Branch (1985) showed that, from the historical records only, one cannot decide whether Kepler's SN light curve was more appropriate for a Type I or for a Type IIL. The magnitude at the optical maximum is not well defined for this class; however, in the case of SN 1980k, a recent Type IIL SN, the absolute magnitude at maximum was -18.5 (Tammann 1982). Moreover, the radio light curve implied $\dot{M}/w \approx 4 \times 10^{-7}$ $(M_\odot\ \mathrm{yr}^{-1})/(\mathrm{km\ s}^{-1})$ (see Panagia 1985); both values are similar to those obtained for the Type Ib SNe; therefore they do not discriminate one SN type from the other.

Even more uncertain is the nature of the progenitor. While searching for candidates, however, a parameter that is worth taking into consideration is the velocity of Kepler's SN progenitor. On the observational basis it leads to considering classes of know runaway objects, while on the theoretical basis it suggests investigating evolutionary paths ending with runaway stars, or systems.

A mechanism which has generally accounted for runaway stars is the explosion of a member of a close binary system. The evolution of massive binary systems has been studied by several authors (Tutukov and Yungelson 1973; de Loore and de Greve 1975; van den Heuvel 1976): the primary star evolves faster but, before exploding, transfers part of its mass to the companion, becoming then the less massive component; for this reason the SN does not disrupt the system. After the SN event the system is composed of a neutron star and a massive main-sequence star that in turn will evolve into a SN.

The kick received by the system depends on how close the two components were before the former explosion. Sutantyo (1973) computed the runaway velocities following a SN explosion in a binary; his result can be rewritten as

$$U = \sqrt{G(M_1 + M_2)/R}\, M_2/(M_1 + M_2)(M_1 - M_r)/(M_1 + M_r)\ ,$$

where M_1 is the mass of the exploded star, M_r that of the stellar remnant, M_2 that of the companion, and R the original orbital radius. If $M = M_2 \approx M_1 \gg M_r$, $U = 220(M/M_\odot)^{1/2}/(R/R_\odot)$ km s^{-1}. Therefore, only under extreme conditions velocities like that of Kepler's SNR progenitor will be obtained by this mechanism. However, there is some observational evidence for the existence of other objects with spatial velocities too high (up to 200 km s^{-1}) to be easily explained.

The two best known classes of Population I runaway objects are runaway OB stars and binary Wolf-Rayet (W-R) stars. Both naturally fit into the standard evolutionary scheme for close massive binary systems (van den Heuvel 1976); they may represent two different stages of that scheme. In the following I shall consider in detail only the latter class, which shows some striking similarities with the progenitor depicted for Kepler's SNR.

By a spectroscopic search of W-R stars, one can select single-line spectroscopic binaries, where the unseen companion is thought to be a compact object, possibly a neutron star. Most of these W-R stars belong to the WN class, and are classified as young population stars (Moffat 1983). Hidayat, Admiranto, and van der Hucht (1984) investigated the distribution of single-line binaries across the Galactic plane; it is rather peculiar; while single W-R stars and double-line binaries have a dispersion of ~ 100 pc, the average z of the known single-line binaries is 279 pc, with objects up to nearly 1000 pc away from the plane. The high values of z are by themselves a proof of the runaway nature for these W-R stars: to reach such large z in a few million years (the commonly accepted age for these objects), velocities larger than 100 km s^{-1} are required. Direct measurements of radial velocities are rather uncertain, due to the broadness of emission lines, and to the poorly known distance; nonetheless, in a few cases, significant lower limits have been put.

Another interesting characteristic of this class of W-R stars is the association with the so-called "ring nebulae." These nebulae have been interpreted as due to some kind of "interaction between the central star and the ambient interstellar medium" (Chu 1981). I suggest that some of them are composed of circumstellar matter that formed a bow shock, pushing against the interstellar flow, and there became denser and clumped. For these nebulae, the following characteristics must coexist:

i) A brighter limb (in the direction of the stellar motion) is present;

ii) The nebula is highly clumped, with peak densities up to 10^3 cm^{-3};

iii) The star is displaced toward the brighter limb (the apex of the bow shock) and participates in its motion;

iv) The related star is a W-R runaway (high z, large radial velocity, unseen companion).

Here are the best candidates:

1. M1-67, associated with the W-R star 209 BAC. This star is famous for being the fastest known runaway W-R star; a lower limit to its peculiar velocity is 178 km s^{-1}. As expected for runaway W-R stars, it is a single-line spectroscopic binary (Moffat, Lamontagne, and Seggewiss 1982). The nebula has a highly inhomogeneous texture, with densities up to more than 10^3 cm^{-3} (Chu and Treffers 1981). Spectroscopic study in Hα (Solf and Carsenty 1982) revealed two components, one redshifted (stronger, and more concentrated), and the other blueshifted (weaker, and more diffuse) which have been interpreted as an expanding shell, with an expansion velocity of 42 km s^{-1}, and an average heliocentric radial velocity of $+158$ km s^{-1}; therefore the brighter side is in the direction of the stellar motion. The stellar velocity is $+175 \pm 200$ km s^{-1}; it is closer to that of the stronger (redshifted) component. For these reasons it seems likely that the optical knots do not in fact

belong to an expanding shell, but that they are located on the surface of a bow shock, pointing away from us.

2. S308, associated with HD 50896. This nebula is almost circular and has a brighter limb on the NW side. The W-R star is slightly displaced toward the brighter limb. The nebula is filamentary, with not very high densities (<50 cm^{-3}; Kwitter 1981). The associated W-R star is a single-line spectroscopic binary, as typical for W-R runaway stars. Chu *et al.* (1982) explored the possibility of a runaway nature: in this case NGC 2362, the only cluster in the vicinity, is a strong candidate as the birthplace, while the W-R star should have moved faster than 150 km s^{-1} to reach its present position. But the authors discarded this possibility due to "the near-central location of the star in the nebula"; their argument is, however, not valid if the nebula originated from a stellar wind, since in this case it should participate in the stellar motion. The circular shape of the nebula and the absence of very dense knots suggest that, in this object, the interaction with the interstellar medium did not develop until the stationary phase of a bow shock. However, a brighter limb, and the displacement of the W-R star toward that limb argue in favor of the model presented above. A further indication is the direction of the brighter limb, opposite that of NGC 2362, as if the W-R star is actually moving away from that cluster.

3. NGC 6888, associated with HD 192163. This star too is a single-line spectroscopic binary. The nebula has an elliptical shape with a strongly developed filamentary structure (Wendker *et al.* 1975), with densities reaching 400 cm^{-3} (Kwitter 1981). The star is located near the brighter side, pointing in the NW direction. Assuming that this is the direction of the stellar motion, the star is moving away from the Galactic plane.

4. NGC 3199, associated with HD 89358. The nebula has an almost paraboloidal shape, as expected for a well-developed bow shock (see Chu, Treffers, and Kwitter 1983). The star is close to the apex that is also the brightest part of the nebula. The apex is directed away from the Galactic plane. On the opposite direction, almost on the plane, there is the cluster NGC 3293, from which the W-R star possibly originated. It is worthwhile to check whether also this star is a single-line spectroscopic binary.

Therefore these nebulae have many properties that correspond to the picture drawn for Kepler's SN progenitor. However, there is still an argument against a W-R progenitor for Kepler's SN: the wind velocity, determined in § III, is more than an order of magnitude lower than inferred for W-R stars by UV measurements. A wind velocity of a few tens of kilometers per second would instead be typical for red supergiants. Such a paradox is avoided if the wind parameters changed during the stellar evolution, for instance, the star could have evolved, before exploding, from a red supergiant to a W-R star. A nebula formed when the wind was slow, and at that time knots developed with a high-density contrast. The subsequent fast W-R wind blew out that nebula; however, compact knots have not been accelerated efficiently by that wind.

An object for which an evolution from red supergiant to W-R star has been suggested is P Cygni. By a comparison with theoretical evolutionary tracks, and with other P Cygni type stars, Lamers, de Groot, and Cassatella (1983) predicted that P Cygni will evolve to a WN star. Wendker (1982) suggested a bow shock model to explain an arc of radio emission observed near the star in the direction of its peculiar motion; according to Lamers, de Groot, and Cassatella (1983), the transverse velocity of P Cygni is 140 km s^{-1}. Then P Cygni (and other stars like it) could well represent an evolutionary stage of an object like Kepler's SN progenitor. The only missing points are a high z and a compact, close companion; however, to my knowledge, no specific search for a companion in P Cygni type stars has been attempted yet.

If a P Cygni type star represents an intermediate phase between a red supergiant and a WN star, one would predict also the existence of binary, runaway red supergiants, which in some cases have already developed a nebula at the bow shock.

If the scenario presented is correct, one may wonder what kind of stellar remnant has been left after Kepler's SN. One expects at least one old neutron star. Under the hypothesis that also the second explosion has formed a neutron star, the system will be disrupted if the final mass of the progenitor was more than 3 times that of a neutron star. Otherwise a binary system with an eccentric orbit is expected—since after the latter explosion neither friction nor accretion will act to make it circular. Two such systems are known, namely the binary pulsars PSR 1913+16 (Hulse and Taylor 1975) and PSR 2303+46 (Stokes, Taylor, and Dewey 1985). While the other three binary pulsars known have orbital eccentricities close to zero, their eccentricities are 0.617 and 0.658, respectively.

As Kepler's SNR, also PSR 2303+46 is located 500 pc away from the Galactic plane: assuming a velocity of 25 km s^{-1}, Stokes, Taylor, and Dewey (1985) derived an evolution time larger than 2×10^7 yr. However, an object with such a low velocity would have not been able to move so far from the Galactic plane; therefore its velocity must be higher, and the analogy with the case of Kepler's SNR becomes more evident.

Therefore one, or two, neutron stars should be present near the center of Kepler's SNR. However, the lack of detection of any stellar remnant in X-ray puts an upper limit of nearly 2×10^6 K to the neutron star temperature (Helfand, Chanan, and Novick 1980). A deeper X-ray search is needed for a more significant test of the presence of a stellar remnant in Kepler's SNR.

VII. SUMMARY

In this paper I assumed that the optically emitting knots of Kepler's SNR consist of circumstellar material; by averaging their proper motions one can then estimate the velocity of the SN progenitor (350 km s^{-1}). At such a velocity, the ram pressure of the interstellar medium is effective to deflect the wind flow, and to form a bow shock.

Various features observed in Kepler's SNR can be explained assuming that the SN blast wave is presently moving through the bow shock: the brighter northern limb, in the direction of the progenitor's motion; the absence of a sharp limb on the southern region, for Sedov expansion of the blast wave; the presence of high-density knots, due to instabilities.

This model allows one to derive when the progenitor got its runaway velocity ($\sim 3 \times 10^6$ yr ago), to estimate the wind parameters ($\dot{M} \sim 5 \times 10^{-5}$ $M_\odot$ yr^{-1}; $w \sim 10$ km s^{-1}), and to give a lower limit to the total mass lost as wind (>10 $M_\odot$). Furthermore, an absolute measurement of Kepler's SNR distance ($\sim$4.5 kpc) has been attained. A young, massive progenitor is depicted, subject to strong mass loss, with low wind velocity.

Kepler's SN progenitor fits well in evolutionary scenarios for close, massive binary systems. There are similarities with runaway W-R stars, surrounded by ring nebulae: in these nebulae the matter is typically anisotropic and highly clumped, as in Kepler's SNR. Such stars possibly evolved from P Cygni type stars, which also can possess runaway velocities, and be associated to ring nebulae.

Finally, some binary neutron stars could be explained as remnants of events like Kepler's SN. In this case one, or maybe two neutron stars should be found by a deeper X-ray search near the centre of Kepler's SNR.

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