A Massive Star Odyssey, from Main Sequence to Supernova
Proceedings IAU Symposium No. 212, © 2003 IAU
K.A. van der Hucht, A. Herrero & C. Esteban, eds.

Aspherical supernova explosions

Peter A. Höflich[1], Dietrich Baade[2], Alexei M. Khokhlov[3], Lifan Wang[4], and J. Craig Wheeler[1]

[1]*Department of Astronomy, University of Texas, RLM 15.308, C-1400, Austin, TX 78712, USA*
[2]*European Southern Observatory, Karl-Schwarzschild-Straße 2, D-85748 Garching-bei-München, BRD*
[3]*Naval Research Laboratory, 4555 Overlook Avenue, SW, Washington, DC 20375-5352, USA*
[4]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA*

Abstract. Core collapse supernovae (SN) are the final stages of stellar evolution in massive stars during which the central region collapses, forms a neutron star (NS), and the outer layers are ejected. Recent explosion scenarios assumed that the ejection is due to energy deposition by neutrinos into the envelope, but detailed models do not produce powerful explosions. There is new and mounting evidence for an asphericity and, in particular, for axial symmetry in several supernovae which may be hard to reconcile within the spherical picture. This evidence includes the observed high polarization and its variation with time, pulsar kicks, high velocity iron-group and intermediate-mass elements material observed in remnants, direct observations of the debris of SN 1987A, *etc.* Some of the new evidence is discussed in more detail. To be in agreement with the observations, any successful mechanism must invoke some sort of axial symmetry for the explosion. We consider jet-induced/dominated explosions of core collapse supernovae. Our study is based on detailed 3-D hydrodynamical and radiation transport models. We find that the observations can be explained by low velocity, massive jets which stall well within the SN envelope. Such outflows may be produced by MHD-mechanisms, convective dominated accretion disks on the central object or asymmetric neutrino emissions. Asymmetric density/chemical distributions and, for SN 2002ap, off-center energy depositions have been identified as crucial for the interpretation of the polarization.

1. Introduction

There is a general agreement that the explosion of a massive star is caused by the collapse of its central parts into a neutron star or, for massive progenitors, into a black hole. The mechanism of the energy deposition into the envelope is still debated. The process likely involves the bounce and the formation of the prompt shock (*e.g.*, Van Riper 1978), radiation of the energy in the form of neutrinos (*e.g.*, Bowers & Wilson 1982), and the interaction of the neutrino with the material of the envelope and various types of convective motions (*e.g.*, Herant *et al.* 1994; Burrows *et al.* 1995; Müller & Janka 1997; Fryer & Warren 2002), rotation (*e.g.*, LeBlanc & Wilson 1970; Mönchmeyer *et al.* 1991) and magnetic

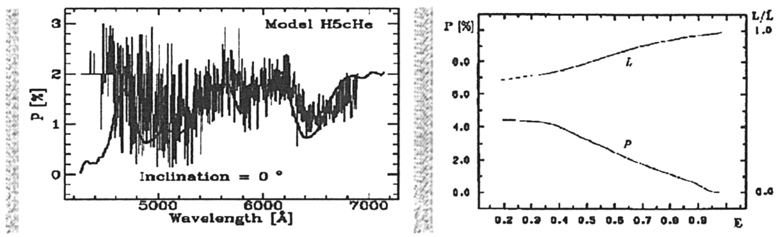

Figure 1. *Left:* polarization spectrum for SN 1993J for an axis ratio of 1/2 for an oblate ellipsoid in comparison with observations by Trammell *et al.* (1993). *Right:* the dependence of the continuum polarization and directional dependence of the luminosity is shown as a function axis ratios for oblate ellipsoids seen from the equator (from Höflich 1991; Höflich *et al.* 1995).

fields (*e.g.*, LeBlanc & Wilson 1970; Bisnovatyi-Kogan 1970; Symbalisty 1984). Currently, the most favored mechanism invokes the neutrino deposition, but it is neither clear whether it can provide powerful explosions, can account for large scale asymmetries or for large kick velocities as observed in neutron stars (see below). Likely, a quantitative model of the core collapse must eventually include all the elements mentioned above (Höflich *et al.* 2001). In this paper we study the effects and observational consequences of an asymmetric, jet-like deposition of energy inside the envelope of SN.

2. Evidence for asymmetry

In recent years, there has been a mounting evidence that the explosions of massive stars (core collapse supernovae) are highly aspherical:
(*i*) The spectra of core-collapse supernovae (*e.g.*, SN 1987A, SN 1993J, SN 1994I, SN 1999em, SN 2002ap) are significantly polarized at a level of 0.5 to 3 % (*e.g.*, Figure 1; Méndez *et al.* 1988; Cropper *et al.* 1988; Höflich 1991; Jeffrey 1991; Wang *et al.* 1996) indicating aspherical envelopes by factors of up to 2 (Figure 2). The degree of polarization tends to vary inversely with the mass of the hydrogen envelope, being maximum for Type Ib/c events with no hydrogen (Wang *et al.* 2001). For SNe II, Leonard *et al.* (2000) and Wang *et al.* (2001) showed that the polarization and, thus, the asphericity increase with time. Both trends suggest a connection of the asymmetries with the central engine. For supernovae with a good time and wavelength coverage, the orientation of the polarization vector tends to stay constant both in time and with wavelength. This implies that there is a global symmetry axis in the ejecta (Leonard *et al.* 2000; Wang *et al.* 2001).
(*ii*) Observations of SN 1987A showed that radioactive material was brought to the hydrogen rich layers of the ejecta very quickly during the explosion (*e.g.*, Lucy 1988).
(*iii*) The remnant of the Cas A supernova shows rapidly moving oxygen-rich matter outside the nominal boundary of the remnant and evidence for two oppositely directed jets of high-velocity material (Fesen & Gunderson 1996).
(*iv*) Recent X-ray observations with the *Chandra* satellite have shown an unusual distribution of iron and silicon group elements with large scale asymmetries in

https://doi.org/10.1017/S0074180900212473 Published online by Cambridge University Press

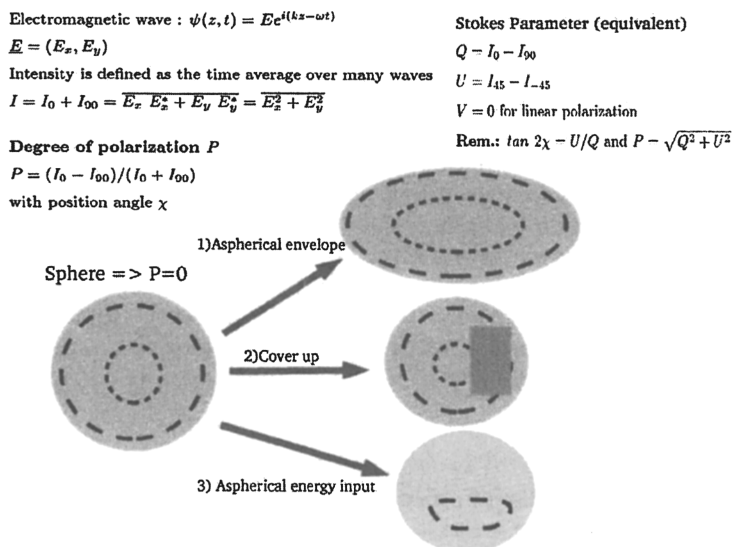

Figure 2. Definition of the polarization and schematic diagram for its production. The dotted lines give the main orientation of the electrical vectors. For an unresolved sphere, the components cancel out. Three main mechanisms can be distingished. $\bar{P}$ can be caused by (*i*) an aspherical envelope; (*ii*) shading parts of the disk; or by (*iii*) an aspherical excitation/ionization.

Cas A (Hughes *et al.* 2000).
(*v*) After the explosion, neutron stars are observed with high velocities, up to 1 000 $\mathrm{km\,s^{-1}}$ (Strom *et al.* 1995).
(*vi*) Direct *HST* images of June 11, 2000, are able to resolve the inner debris of SN 1987A showing its prolate geometry with an axis ratio of ∼ 2, and spectra indicate that the products of stellar burning (O, Ca, *etc.*) are concentrated in the equatorial plane (Höflich *et al.* 2001; Wang *et al.* 2002).

3. Jet-induced supernovae and observations

In SNe, electron scattering is the main mechanism to polarize the light. It can be caused by asymmetries in the density, abundances or excitation structure of an envelope. In general, the supernovae ejecta cannot be spatially resolved. Although the light from different parts of a spherical disk is polarized, the resulting polarization $\bar{P}$ is zero for the integrated light (Figure 2). To produce $\bar{P}$, three basic configurations must be considered: the envelope is aspherical, parts of the disk are shaded, or the envelope may be illuminated by an off-center light source. In the second case, the shading may be either by a broad-band absorber such as dust or a specific line opacity. In the latter case, this would produce a change of $\bar{P}$ in a narrow line range (Figure 4). In reality, a combination of all cases are realized (see below). Note that quantitative analyses of SNe (Figure 1) need to take into account that the continua and lines are formed in the same layers. We have numerically studied the explosion of core collapse supernovae caused by supersonic jets generated in the center of the star to ask for the jet-properties needed to reproduce observations. The initial stellar structures are based on stellar evolution calculations by Straniero *et al.* (1997). The explosion and jet propagation are calculated by a full 3-D code within a cubic domain. The Euler equations are integrated using an explicit, second-order accurate, Godunov type (PPM, Collela & Woodward 1984), adaptive-mesh-refinement, massively parallel, Fully-Threaded Tree (FTT) program, ALLA (Khokhlov 1998). The subsequent evolution, LCs and spectra are calculated by using modules of our hydrodynamical radiation transport code for spherical and full 3-D (HYDRA) (Höflich 2003). This code includes modules for hydrodynamics using PPM (without mesh refinement), detailed networks for nuclear processes and for atomic, non-LTE level populations, and radiation transport (with mesh-refinement). Its components have been used to carry out many of the previous calculations to analyse light curves, flux and polarization spectra of thermonuclear and core collapse supernovae (Höflich 1988 - 2003).

3.1. General results

We simulated the process of the jet propagation through the star, the redistribution of elements, and radiation transport effects. Qualitatively, the jet-induced picture allows to reproduce the polarization observed in core collapse supernovae. Both asymmetric ionization and density/chemical distributions are crucial for the production of $\bar{P}$. Even within the picture of jet-induced explosion, the latter effect alone cannot (!) account for the large $\bar{P}$ produced in the intermediate H-rich layers of core-collapse SN with a massive H-rich envelopes (*e.g.*, SN 1987A, SN 1999em).

A strong explosion and a high efficiency for the conversion of the jet energy requires low jet velocities or a low, initial collimation of the jet. With increasing extension of the envelope, the conversion factor increases. Typically, we would expect higher kinetic energies in SNe II compared to SNe Ib/c if a significant amount of explosion energy is carried away by jets. Within the framework of jet-induced SN, the lack of this evidence suggests low jet-velocities. The He, C, O and Si rich layers of the progenitor show characteristic, butterfly-shape structures, and jets bring heavy elements, *e.g.*, ^{56}Ni, into the outer layers. Due to the high entropies of the jet material close to the center, this may be a possible site for r-process elements. Moreover, aspherical explosion models show a significantly increased fall-back of material on the central object, *e.g.*, a neutron star, on time scales of minutes to hours which may trigger the delayed formation of a black hole. Fallback and the low velocity material may alter the escape probability for γ-rays produced by radioactive decay of ^{56}Ni which is critical for mass estimates of ^{56}Ni, which are based on late time observations (*e.g.*, SN 1998bw). For more details, see Khokhlov *et al.* (1999) and Höflich *et al.* (2001).

3.2. SN 1987A and SN 1999em

In our models for these SNe II, the jet material stalls within the expanding envelope corresponding to a velocity of $\sim 4\,500\,\mathrm{km\,s^{-1}}$ during the phase of homologous expansion. In SN 1987A, a bump in spectral lines of various elements has been interpreted by material excited by a clump of radioactive ^{56}Ni (Lucy 1988). Within our framework, this bump may be a measure of the region where the jet stalled. This could also explain the early appearance of X-rays in SN 1987A,

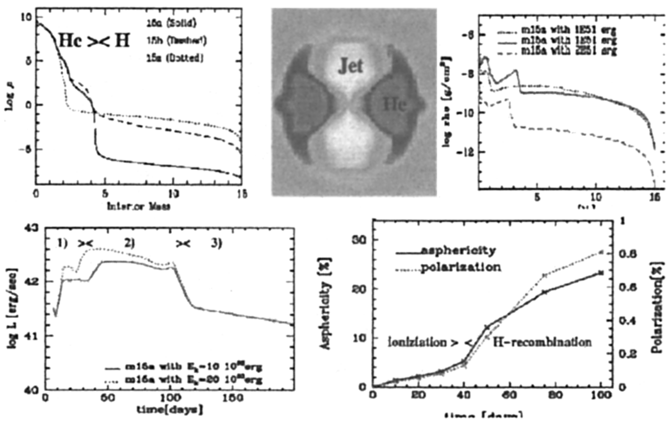

Figure 3. Polarization produced by an aspherical, chemical distribution for an extreme SN IIp model such as SN 1999em.

which requires strong mixing of radioactive material into the hydrogen-rich layers, and the overall distribution of elements in the resolved *HST* images of the inner debris of SN 1987A. For both SN 1987A and SN 1999em, aspherical excitation by hard radiation is found to be crucial to explain the size and presence of the polarization observed early on (Figure 4). For the extreme SN IIp SN 1999em (Figure 3), our model is based on a star with $15\,M_\odot$ and an explosion energy of 2×10^{51} erg. The initial density profile is given for a star at the final stage of stellar evolution for metallicities Z of 0.02, 0.001 and 0 (models 15a, 15b, 15z, upper left panel). For the explosion, we use model 15a. In the upper middle panel, the chemical distribution of He is given at 250 s for the He-rich layers after the jet material has stalled. The gray tones between white and black correspond to He mass fractions between 0 and 1 in a linear scale. The subsequent explosion has been followed in 1-D up to the phase of homologous expansion. In the upper right panel, the density distribution is given at about five days after the explosion. The steep gradients in the density in the upper right and left panels are located at the interface between the He-core and the H-mantel. In the lower left panel, the resulting bolometric LCs are given for explosion energies of 2×10^{51} erg (dotted line) and 1×10^{51} erg, respectively. Based on full 3-D calculations for the radiation and γ-ray transport, we have calculated the location of the recombination front (in non-LTE) as a function of time. The resulting shape of the photosphere is always prolate. The corresponding axis ratio and the polarization seen from the equator are shown (lower right panel). Note the strong increase of the asphericity after the onset of the recombination phase between day 30 to 40 (Höflich *et al.* 2001). For the polarization in a massive, H-rich envelope, $\bar{P}$ is directly liked to the recombination process and asymmetric excitation.

3.3. Supernova SN 2002ap in M 74

SN 2002ap has attracted much attention because early spectra showed a lack of hydrogen and helium characteristic of SN Ic and broad velocity components

https://doi.org/10.1017/S0074180900212473 Published online by Cambridge University Press

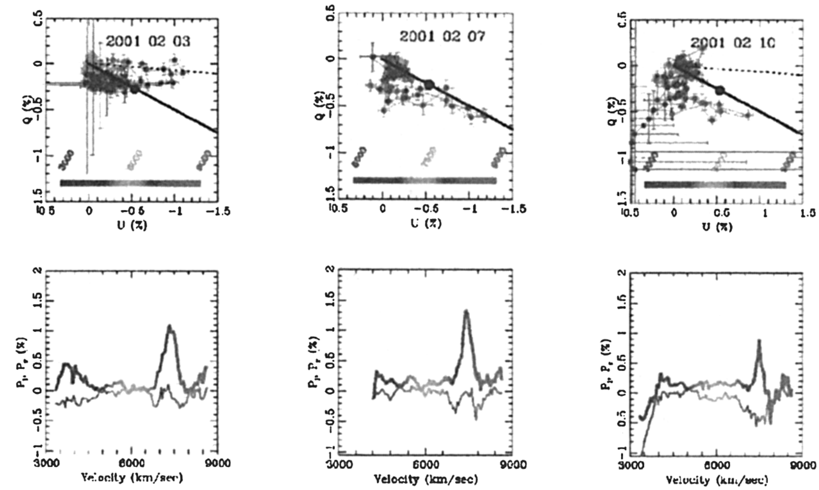

Figure 4. Spectropolarimetry of SN 2002ap at about −6 d, −2 d and +1 d relative to maximum light in V. An intrinsic polarization component (shown as a solid dot) is subtracted from the observed Stokes parameters so that the data points present the intrinsic polarization of the SN. The dashed line illustrates the dominant axis of the polarization. There has been a distinct shift and, perhaps, a small rotation of the axis in the Q-U plane during the early epochs, and the spectra are dominated by Fe II, Na I D and O I. In the spectrum at about 1d after maximum, the original, dominant axis has shifted further in the Q-U plane, and a new axis starts to appear at an angle of about 110° defined by Ca II H&K and the Ca II IR triplet.

(Kinugasa *et al.* 2002; Meikle *et al.* 2002; Gal-Yam *et al.* 2002), which have been taken as one characteristic of 'hypernovae'. The nature, existence of, and importance of 'hypernovae' remains to be clarified, and the study of SN 2002ap presents an important opportunity to shed light on the general category of 'hypernovae', and their relation to typical SNe Ic such as SN 1994I. High-quality spectropolarimetry (range 4170 - 8600 Å; spectral resolution 12.7 Å) of SN 2002ap was obtained with the ESO Very Large Telescope Melipal-FORS1 at three epochs that correspond to −6 d, −2 d, and +1 d for the V maximum of February 9, 2002. The polarization spectra show three distinct broad ($\sim$1000 Å) features at $\sim$4000, 5500, and 7500 Å that evolve in shape, amplitude and orientation in the Q-U plane. The continuum polarization grows from nearly zero to $\sim$0.2 %. The 7500 Å feature is polarized at a level $\geq$1 %. We identify the 5500 and 7500 Å features as Na I D and O I λ7774 moving at about 20 000 km s^{-1}. The blue feature may be Fe II. We interpret the polarization evolution in terms of the impact of a bipolar flow from the core that is stopped within the outer envelope of a C/O core and, consequently, the Ca features show up only at about maximum light. The interpretation of a stalled jet is also supported by IR-spectra taken by C. Gerardy and M. Meikle (2002, private communications) which show strong C I lines (9405 and 10700 Å) at expansion velocities of $\sim$15 000 to 25 000 km s^{-1}, but not, as in SNe Ia, the strong 16000 to 19000 Å feature due to Fe/Co/Ni. Although the symmetry axis remains fixed, the photosphere retreats by different amounts in different directions due to the asymmetric velocity flow and density distribution geometrical blocking effects leading to a continuous shift with time of the main axis of polarization. At about maximum light, the appearance of an additional axis in a Q-U plane due to Ca and processed material indicates a second axis of symmetry. Qualitatively and within the picture of jet-induced supernovae, this may be explained by bipolar-jets which are not perfectly aligned and, thus, produce a kick of the central region (*e.g.*, neutron star and processed material). Detailed radiation-hydro calculations are under way. We conclude that the features that characterize SN 2002ap, specifically its high velocity, can be accounted for in an asymmetric model with a larger ejecta mass than SN 1994I such that the photosphere remains longer in higher velocity material. The characteristics of 'hypernovae' may be the result of orientation effects in a mildly inhomogeneous set of progenitors, rather than requiring an excessive total energy or luminosity. In the analysis of asymmetric events with spherically symmetric models, it is probably advisable to refer to 'isotropic equivalent' energy, luminosity, ejected mass, and nickel mass. This aspect may also be relevant for the interpretation of the hypernova SN 1998bw.

Acknowledgments. The authors are grateful to the European Southern Observatory for the generous allocation of observing time. They especially thank the staff of the ESO Paranal Observatory for their competent and untiring support. This work was supported in part by NASA Grant NAG5-7937 to PAH.

References

Bisnovatyi-Kogan, G.S. 1970, Astron. Zh. 47, 813 (= 1971, Soviet Astron. 14, 652)
Bowers, R.L., Wilson, J.R. 1982, ApJS 50, 115
Burrows, A., Hayes, J., Fryxell, B. 1995, ApJ 450
Colella, P., Woodward, P.R. 1984, J. Comp. Phys. 54, 174
Cropper, M., Bailey, J., McCowage, J., Cannon, R., Couch, W. 1988, MNRAS 231, 685
Fesen, R.A., Gunderson, K.S. 1996, ApJ 470, 967
Fryer, C.L., Warren, M.S. 2002, ApJ (Letters) 574, L65
Gal-Yam, A., Shemmer, O., Dann, J. 2002, IAU Circular No. 7811, 3
Herant, M., Benz, W., Hix, W.R., Fryer, C.L., Colgate, S.A. 1994, ApJ 435, 339
Höflich, P.A. 1988, PASP 7, 434
Höflich, P.A. 1991, A&A 246, 481
Höflich, P.A. 1995, ApJ 443, 89
Höflich, P.A., Wheeler, J.C., Hines, D., Trammell, S. 1995, ApJ 459, 307
Höflich, P.A., Khokhlov, A., Wang, L. 2001, in: J.C. Wheeler & H. Martel (eds.), *20th Texas Symposium on Relativistic Astrophysics*, AIP-CP 586, 459
Höflich, P.A. 2003, in: I. Hubeny, D. Mihalas & K. Werner (eds.), *Stellar Atmosphere Modeling*, ASP-CS in press (astro-ph/0207103)
Hughes, J.P., Rakowski, C.E., Burrows, D.N., Slane, P.O. 2000, ApJ (Letters) 528, 109
Jeffrey, D.J. 1991, ApJ 375, 264
Kinugasa, K., Kawakita, H., Ayani, K., *et al.* 2002, IAU Circular No. 7811, 1
Khokhlov, A.M. 1998, J. Comp. Phys. 143, 519

Khokhlov, A.M., Höflich, P.A., Oran, E.S., Wheeler, J.C., Wang, L., Chtchelkanova, A.Yu. 1999, ApJ (Letters) 524, L107

Leonard, D.C., Filippenko, A.V., Barth, A.J., Matheson, T. 2000, ApJ 536, 239

LeBlanc, J.M., Wilson, J.R. 1970, ApJ 161, 541

Lucy, L.B. 1988, in: M. Kafatos (ed.), *Supernova 1987A in the Large Magellanic Cloud*, Proc. 4th George Mason Astrophysics Workshop (Cambridge: CUP), p. 323

Meikle, P., Lucy, L.B., Smartt, S.J., *et al.* 2002, IAU Circular No. 7811, 2

Méndez, M., Clocchiatti, A., Benvenuto, O.G., *et al.* 1988, ApJ 334, 295

Mönchmeyer, R., Schäfer, G., Müller, E., Kates, R.E. 1991, A&A 246, 417

Müller, E., Janka, H.T. 1997, A&A 317, 140

Straniero, O., Chieffi, A., Limongi, M. 1997, ApJ 490, 425

Strom, R., Johnston, H.M., Verbunt, F., Aschenbach, B. 1995, Nature 373, 590

Symbalisty, E.M.D. 1984, ApJ 285, 729

Trammell, S., Hines, D., Wheeler, J.C. 1993, ApJ 414, 21

Van Riper, K.A. 1978, ApJ 221, 304

Wang, L., Wheeler, J.C., Li, Z., Clocchiatti, A. 1996, ApJ 467, 435

Wang, L., Howell, A., Höflich, P.A., Wheeler, J.C. 2001, ApJ 550, 1030

Wang, L., Wheeler, J.C., Höflich, P.A., *et al.* 2002, ApJ 579, 671

Discussion

KAPER: For three GRBs, afterglow polarization levels of a few percent are observed, very similar to the level of polarization of the supernovae. To explain the polarization of GRB afterglows, it has been suggested that intrinsic polarization due to the synchrotron emission mechanism (up to 60%) plays a role. Alternatively, also in GRB afterglows the observed polarization might be due to asphericity (as in SNe). What is your opinion about this?

HÖFLICH: The optical afterglow is produced by the relativistic jet with $\gamma > 1$, *i.e.*, $v \approx c$. Thus, even if γ varies over the inclination, this hardly produces a large, geometrical asymmetry. *If* there is an underlying SN, its contribution is not dominant for the light (or for a short period only). I think the synchrotron mechanism is probably correct for GRBs. For SN, photospheric lines modify $\bar{P}$.

KUDRITZKI: Peter, I am surprised. You do 3-D hydro-calculations, but you always obtain the butterfly symmetry. Does that mean that there are no instabilities?

HÖFLICH: There are instabilities for high velocity, low density jets. Basically, instabilities occur if the transversal sound traveling times become shorter than the times a jet operates, as you have seen in one of the figures. However, these models do not reproduce the observations, whereas low velocity, high-density jets do.