Title

PROGENITORS AND BIRTH-RATES OF CATACLYSMIC VARIABLES AND TYPE-I SUPER-NOVAE

Journal

OBSERVATORY, 102(1049)

ISSN

0029-7704

Author

TRIMBLE, V

Publication Date

1982

hole. Pairs are created on 'empty' (vortex-funnel) field lines by photon–photon collisions at a rate far in excess of that needed to maintain a force-free magnetosphere. If the extracted power L_b is given entirely to pairs so created (by a luminosity of MeV γ-rays L_c) around a black hole of mass $10^8\,M_8$ solar masses, the resulting flow will have a bulk Lorentz factor $\gamma_b = 10^5 M_8 (L_b/10^2 L_c)/(L_c/10^{40}$ ergs per second). Annihilation is unimportant in such beams. Even if it does occur in much denser jets, giving directed γ-ray beams, all is not lost, for the γ-rays of sufficiently powerful beams can be reconverted to pairs at about 0·1 parsec by photon–photon collisions with bremsstrahlung X-rays from nuclear gas.

The observations described this morning indicate that jets have bulk Lorentz factors of a few on parsec scales but have velocities much less than c on galactic scales. In a channel of constant area, a supersonic flow which sweeps up sufficient stationary material to double its mass-flux will become transonic. If the flow is to be recollimated into a new supersonic (but now slower) jet, the external pressure in the region of entrainment must be able to support the full ram pressure of the desired jet. This is a severe constraint, as the pressures deduced from models of accretion flows and observations of broad- and narrow-line regions of quasars and radio galaxies (covering, say 10^{-3} to 10^4 parsecs) are insufficient to allow recollimation of high-power jets, especially if they are non-relativistic. When the external pressure *is* adequate, entrainment may make the flow subsonic, necessitating recollimation in a fluid nozzle. On the other hand, if the external pressure falls sufficiently rapidly, for suitably adjusted rates of entrainment there exist simple flows which remain supersonic as the mass flux tends to infinity, while the bulk velocity and divergence angle of the flow tends to zero. The entrained material may be mass lost from stars in the jet, or it may be matter carried in by boundary instabilities.

PROGENITORS AND BIRTH-RATES OF CATACLYSMIC VARIABLES AND TYPE I SUPERNOVAE

By Virginia Trimble
University of California; University of Maryland

Cataclysmic variables and Type I supernovae apparently arise from rather similar parent systems; but the latter must do so with an efficiency approaching unity, while 1 per cent efficiency suffices for the former.

Currently promising models of cataclysmic variables and Type I supernovae suggest that they arise, at least partially, from rather similar kinds of binary systems. These consist[1–6] of a degenerate dwarf with a companion close enough to transfer material onto it. The Type I supernovae (surely) and the cataclysmic variables (probably) belong to a disk (but not spiral arm) population, and so should have lifetimes less than the age of the Galaxy.

The phenomenological difference between the two classes is in what happens to the transferred gas. To look like a nova (main-sequence donor) or recurrent nova (giant donor), a degenerate dwarf must burn hydrogen in a hydrodynamical thermal runaway, so as to expel most of the accreted hydrogen still unburned. Otherwise, a nova outburst fails to turn off on the observed time-scale. To produce a Type I supernova, on the other hand, the degenerate dwarf must burn accreting hydrogen in such a way as to keep the resultant helium. Otherwise, its mass cannot grow to the critical value at which carbon (or helium) deflagration sets in to make the supernova. This critical value is between 1·1 and 1·4 $M_\odot$ for most of the cases that have been studied[5].

Clearly a system cannot do both things (at least at the same time) unless the degenerate dwarf starts out very close to the critical mass, so that it can be driven over the edge by the $\sim 10^{-3}\,M_\odot$ of accreted hydrogen that actually burns in a nova outburst (and so can be retained). This must be rather rare, as[7] most single stars now dying leave degenerate cores near 0·7 $M_\odot$, and the effect of a close companion is[8] to reduce the remnant mass for a given initial one.

According to the models, the class to which a system will belong is decided largely by the rate at which gas is deposited onto the degenerate dwarf[9–11,6]. Large rates ($\gtrsim 10^{-7}\,M_\odot$/year) result in steady burning; somewhat lower ones in thermal runaways but not explosions; and rates near 10^{-10}–$10^{-9}\,M_\odot$/year in hydrodynamic explosions. These numbers depend somewhat on the mass and temperature of the degenerate dwarf; thus a system may move from one class to the other as the dwarf gains mass from accretion or is heated by nuclear burning, as well as by a changing transfer rate.

Given these points, we may reasonably ask how many ancestral systems are required for each of the two classes and how these numbers compare with the current Galactic birth-rate of binaries that might evolve into the requisite configurations. Type I supernovae occur[12] in galaxies like the Milky Way about once every 60 years.

Novae are a bit more complicated. On average, one or two are spotted a year. This must be corrected for fairly severe, but uncertain, incompleteness, leading to a (somewhat contentious) 10 per year[13,14]. With so high a rate, some systems must go off many times, even if every binary in the Galaxy were capable of nova outbursts. Models suggest the need to accumulate between 10^{-5} and $10^{-4}\,M_\odot$ of transferred material at an accretion rate near $10^{-9}\,M_\odot$/year to trigger a hydrodynamic event. Thus the recurrence time should be 10^4–10^5 years, and the potential number of explosions per system $0{\cdot}5 \times 10^4$ to $0{\cdot}5 \times 10^5$ if about half a solar mass is available for transfer. Thus one system needs to enter the set of nova-makers each 500–5000 years to keep up the supply. Halving this to accommodate other sorts of cataclysmic binaries, we find a birth-rate that still remains roughly an order of magnitude lower than that of Type I supernovae.

Thus in a steady state the Galaxy must provide ancestors for one Type I supernova every 60 years and one cataclysmic variable every 250–2500 years. What does it seem to be doing? We get the most generous estimate by multiplying the current star-formation rate by factors for (*a*) stars with stellar companions, (*b*) the portion of the initial mass function that can make degenerate dwarfs of adequate mass in binaries, and (*c*) the fractions of binaries with initial separations and initial mass ratios that permit mass transfer and common-envelope evolution, but not contact binaries of the W Ursa Majoris type, which have a different sort of evolution[15].

The stellar birth-rate, according to Miller and Scalo[16], is about four per year in a Galactic disk of 15 kpc radius. Of these, about $\frac{2}{3}$ will have stellar companions[17]. A fraction 0·14 will have[16] masses between 1 and 15 $M_\odot$, and so can give suitable degenerate dwarfs in interacting binaries[8]. Finally, the logarithmic distribution of initial binary separations is nearly flat for semi-major axes between 2 and 2000 times the initial stellar radii, the range covered by the factor $\frac{2}{3}$ just mentioned[17]. Thus another factor $\frac{1}{3}$ comes from the requirement for initial separation between about 3 and 30 R_*. And a final factor of $\frac{1}{2}$ represents the fraction of systems with initial mass ratios near unity, so that there will be enough total mass in the system to bring the degenerate dwarf up to the critical mass.

The product of these factors is 0·06 suitable systems born per year, or one each 17 years. Thus only 0·007 to 0·07 of the systems need to evolve to cataclysmic-binary configurations to keep up the supply, but $\frac{1}{4}$–$\frac{1}{3}$ of them are needed to make Type I supernovae. No allowance has been made for any of the details of stellar or binary evolution. The most serious neglect is surely mass loss from the system. This need not much affect cataclysmic-variable formation, as some systems have components considerably under 1 $M_\odot$. But mass loss at any evolutionary stage self-evidently makes building up a critical-mass degenerate dwarf for a Type I supernova more difficult.

Apparently, then, there is no great difficulty in providing adequate supplies of cataclysmic variables *via* either a long-lived stage in a few systems or a short-lived stage in many of them. In the latter case, for instance, the low transfer-rate associated with cataclysmic variables might occur briefly at the onset of mass exchange[6]. The production of Type I supernovae from the ancestral systems, on the other hand, must be rather surprisingly efficient, implying stringent constraints on the details of system evolution, especially mass loss.

Acknowledgements. This work was done at the Institute of Astronomy, Cambridge, whose hospitality is once again gratefully acknowledged. Drs Ray Carlberg, Peter Eggleton, Douglas Gough, Roberto Terlevich and Ron Webbink have kindly listened to my views on this subject, without necessarily agreeing, and supplied some useful numbers, or reasons why they are not well known.

References

(1) J. S. Gallagher & S. Starrfield, *Ann. Rev. A. & A.*, **16**, 171, 1978.
(2) A. D. Mallama & V. Trimble, *Q.J.*, **19**, 430, 1978.
(3) G. T. Bath, *Q.J.*, **19**, 442, 1978.
(4) J. C. Wheeler, *Type I Supernovae* (University of Texas, Austin).
(5) K. Nomoto, *Ap. J.*, **253**, 798, 1982.
(6) I. Iben, *Hot Accreting White Dwarfs in the Quasistatic Approximation* [preprint], 1982.
(7) V. Weidemann, in *White Dwarfs and Variable Degenerate Stars*, edited by H. M. Van Horn & V. Weidemann (University of Rochester), 1979.
(8) R. F. Webbink, in *White Dwarfs* . . .[7], 1979.
(9) B. Paczyński & A. Żytkow, *Ap. J.*, **222**, 604, 1978.
(10) B. Paczyński & B. Rudak, *A. & A.*, **82**, 349, 1980.
(11) G. S. Kutter & W. M. Sparks, *Ap. J.*, **239**, 998, 1981.
(12) G. Tammann, in *Supernovae*, edited by M. J. Rees & R. Stoneham (Reidel, Dordrecht), 1982, p. 371.
(13) S. van den Bergh, private communication, 1976.
(14) V. Trimble, *M.N.*, **178**, 335, 1978.
(15) R. F. Webbink, *Ap. J.*, **227**, 178, 1979.
(16) G. E. Miller & J. M. Scalo, *Ap. J. Suppl.*, **41**, 513, 1979.
(17) H. A. Abt & S. G. Levy, *Ap. J. Suppl.*, **30**, 273, 1976.