Planetary Systems in the Universe - Observation, Formation and Evolution
Proceedings IAU Symposium No. 202, ©2004 IAU
Alan Penny, Pawel Artymowicz, Anne-Marie Lagrange, & Sara Russell, eds.

Episodes of Emission Lines in the Spectra of Red Giants as Signatures of Remnant Planetary Systems

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Abstract. When a star with a mass of about 1 solar mass enters the red giant stage of its evolution, the radius of its atmosphere reaches several astronomical units. If the star possessed during its main-sequence life a planetary system, similar to the solar system, the planets will be embedded into a rather dense and hot medium. Effects of a planet revolving around a red giant at a short distance (inside its circumstellar envelope) are discussed. Systematic monitoring of the spectra of red giants may reveal periodicities in the emergence of shock-induced emission lines and thus to detect probable remnant planetary systems around these stars.

At the end of its evolution, a solar-type star enters the phase of a red giant. Its radius grows from $\sim 1R_\odot$ to a few $10^2 R_\odot$. The star begins to lose matter at a rate of $10^{-7} - 10^{-5} M_\odot$ year^{-1}. An extensive gas-dust circumstellar envelope forms. The red-giant stage is very short as compared to the main-sequence stage; it takes no more than a few hundred thousand years. The ultimate end is a complete loss of the convective shell, formation of a naked white-dwarf core, surrounded by a planetary nebula.

If the star possessed a planetary system during its main-sequence life, at the red-giant stage the closer-by planets, revolving at $R \sim 1 - 3$ A.U., will be embedded within the star's atmosphere. The more massive ones of them will probably survive the red-giant phase (Struck-Marcell 1988).

Evolution of a red giant having a compact stellar companion (a brown/black dwarf with a mass of $\gtrsim 0.02M_\odot$ or possibly a neutron star) was analysed in a series of papers on the 'double-core evolution' (Soker 1999 and references therein). The fate of a lower-mass companion $[(0.001–0.01)M_\odot$ – a planet], embedded in the atmosphere of a star that has become a red giant, was also considered in a number of works. In particular, Soker (1999) proposed to search for Uranus–Neptune-like planets in planetary nebulae, formed in course of the post-AGB evolution.

A planet orbiting around a $1M_\odot$ star at a distance of 1 A.U. would move at velocity $V_p \sim 30$ km s^{-1}. If the star is a red giant, then the planet is embedded in the star's atmosphere, having a temperature $T \sim 2000$ K and particle number density of $\sim 10^{12} - 10^{13}$ cm^{-3}. The velocity of sound a_s there would be about 3.4 km s^{-1}. Thus, the planet's motion is supersonic, the Mach number $\mathsf{M} = V_p/a_s$ being about 9. This motion is similar to a motion of a large meteoritic body in the Earth's atmosphere (Tsikulin 1969). A strong conical shock wave, ionising gas and heating it to 10,000–15,000 K, is formed.

https://doi.org/10.1017/S0074180900217646 Published online by Cambridge University Press

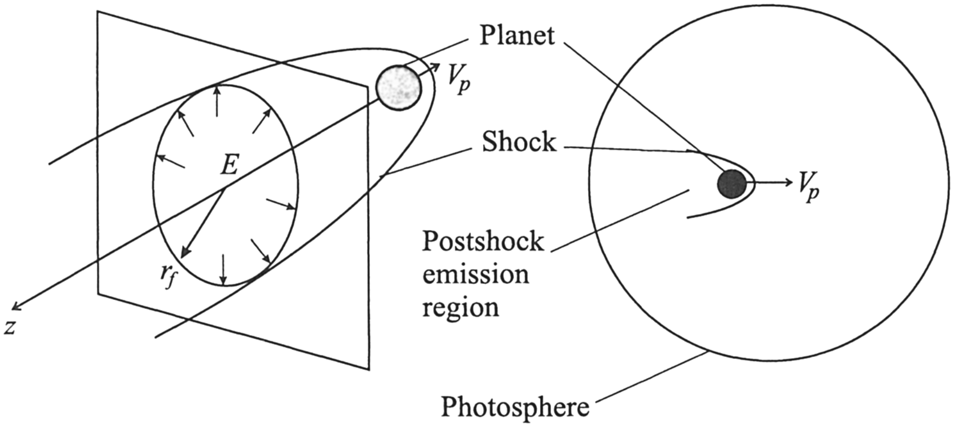

Figure 1. *Left:* Propagation of a shock wave within a slab perpendicular to the body's velocity vector; E is the energy released in this layer. *Right:* Motion of a planet across the disc of a red giant at supersonic velocity V_p.

We consider a simple model, in which a perturbing body with diameter d is moving along a rectilinear trajectory at velocity $V_p > a_s$ through a medium with mass density ρ_0. Quantity E is the energy released at a unit path of the body's motion; E is numerically equal to the drag force exerted on the body by the medium:

$$F = \frac{\pi d^2}{4} \rho_0 V_p^2. \tag{1}$$

Owing to the drag, the planet is gradually spiraling into the red giant's atmosphere. The rate of decrease of its semimajor axis a is (see, e.g., Taam, Bodenheimer & Ostriker 1978):

$$\frac{\dot{a}}{a} = -\frac{F V_p a}{G M_* M_p}. \tag{2}$$

Using (1) and substituting a = 1 A.U., $M_* = 1 M_\odot$, $V_p = 30\ \mathrm{km\,s^{-1}}$ and Jupiter's parameters $M_p = 1 M_J = 1.9 \times 10^{30}$ g, $d = d_J = 1.4 \times 10^{10}$ cm, we have $\dot{a}/a \sim -8 \times 10^{-8}\ \mathrm{year}^{-1}$. Thus, during the red giant stage, which lasts not longer than 10^6 years, the semimajor axis of the planet's orbit decreases by $\lesssim 8\%$. For a larger planet ($13 M_J$, $2.35 d_J$), braking is still smaller, $\lesssim 3.2\%$.

The motion of the planet through the stellar atmosphere is similar to the case of propagation of a shock wave from a detonating cylindrical charge (Tsikulin 1969). That is, in any plane perpendicular to the trajectory of the body, the propagating shock can be considered as a cylindrical one (see Fig. 1). The shock front radius in this plane is

$$r_f = \left(\frac{E}{\rho_0}\right)^{1/4} t^{1/2} \tag{3}$$

with $t = z/V_p$. The front equation in the (r, z) coordinates (Fig. 1, *left*) is

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$$\frac{r_f}{d} = \left(\frac{\pi}{4}\right)^{1/4} \left(\frac{z}{d}\right)^{1/2} \tag{4}$$

Shock velocity D in the direction perpendicular to the trajectory is decreasing with time as

$$D = \frac{1}{2} \left(\frac{E}{\rho_0}\right)^{1/4} t^{-1/2}. \tag{5}$$

For a planet with $d = 2.35 d_J$, velocity D will fall to the velocity of sound a_s at a distance $z_{\max} = d(\pi/4)^{1/2}(\mathsf{M}^2/4) \sim 5.6 \times 10^{11}$ cm behind the body. There will be no emission at greater z's. The corresponding maximum front radius $r_{f\max} = 1.3 \times 10^{11}$ cm. The maximum projected area of the shocked 'cone' (for a side view, as in Fig. 1, *right*) is

$$S_{\rm sh} = \frac{1}{3} (4\pi)^{1/4} d^{1/2} z_{\max}^{3/2} \sim 4.8 \times 10^{22} \text{ cm}^2 \ \sim 1.6 \times 10^{-5} S_*, \tag{6}$$

where $S_* = \pi R_*^2 \sim 3 \times 10^{27}$ cm^2 is the stellar disc area for $R_* \sim 3 \times 10^{13}$ cm. Observations and model calculations of the Balmer emission lines in Miras (e.g., Fox & Wood 1985) show that, for the above-mentioned parameters, the shock front yields up to 10^{20} Hα photons cm^{-2} s^{-1}; with source area $S_{\rm sh}$, this can account for the total Balmer line fluxes observed from a star at a distance of about 300 pc, a few $\times 10^{-12}$ erg cm^{-2} s^{-1} (Fox, Wood & Dopita 1984).

Since 1994, our team has been monitoring a sample of about 20 Miras in the Hα line and in the H_2O maser line at $\lambda = 1.35$ cm (Esipov *et al.* 1999 and references therein). Some stars (R Leo, R Cas and U Aur) displayed isolated bursts of the Hα emission, followed (about a year and a half later) by a flare of the H_2O maser radio emission. This may be due to a periastron shock-wave episode of a planet in a highly eccentric orbit with a period $P \sim 15$ years. Some other stars (e.g., U Ori, Rudnitskij *et al.* 2000) have already shown some hints to H_2O maser 'superperiodicity' of 12–15 years – which could be associated with planetary revolution periods.

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