WINDS OF WOLF–RAYET STARS: PHENOMENOLOGY OF MASS LOSS

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Population I Wolf–Rayet (WR) stars are the evolved descendants of massive ($M \gtrsim 25 M_\odot$) O-type stars. The dense, fast radiatively-driven WR winds efficiently hide all vital information about basic characteristics of the stellar cores. Observing binary systems with WR components, we put firm limits on the sizes and luminosities of WR stars. In attempt to understand dynamics of the outflows, we study the micro-structure of WR winds, finding that they are composed from numerous dense clumps. The growing evidence that WR stars may be linked (collapsars) to the long Gamma Ray Bursters raises a question about rotation rates of WR stars. First results based on the observations of globally-structured winds of some WR stars show that they may be considered as moderately fast rotators. There is one more fascinating feature of the WR mass loss: some carbon-reach WR stars may form dust, thus placing them among the first prodigious dust-producers in the early Universe. Though we are yet to find how dust is formed in the extremely hostile environment of WR winds, we have made substantial progress over the past decade. Recent high spatial resolution near/mid-infrared imaging at the HST, Keck and Gemini, combined with abundant optical/UV spectroscopy and photometry, allows to map rapidly changing environments of the dust-forming regions and derive some basic properties of the freshly formed dust.

INTRODUCTION

Discovered in 1867 by C. J. E. Wolf and G. Rayet, the Population I Wolf–Rayet stars form a rather peculiar class of massive stars whose spectra are completely dominated by broad, intensive emission lines. A gradual improvement of models of stellar evolution helped to realize that the Population I WR stars represent a final evolutionary stage of the massive ($M \geq 25 M_\odot$ for a nearly solar metallicity) O-type stars (see [28] and references therein). WR stars consist of the hot H- (CNO cycle) or He-burning cores that drive very strong winds, making it generally impossible to see the stellar surface (average mass-loss rates $\dot{M} \sim 10^{-5} M_\odot \mathrm{yr}^{-1}$ and terminal velocities $v_\infty \sim 1000-4000\ \mathrm{km\ s}^{-1}$). Due to the extremely high mass loss rates coupled with high wind velocities, WR stars represent a substantial, if not leading, component affecting the "ecology" and structure of the interstellar medium, as well as star formation in galaxies (including what one now calls "Wolf–Rayet galaxies" [7]). WR stars are considered as unequivocal "fiducial marks" of the starburst regions. The combination of high luminosity and sensitivity to Z (relative heavy metal content) makes WR stars excellent tracers of the metallicity gradients in distant galaxies. Rapid evolution of WR stars places them on a verge of exploding as Supernovae (hypernovae), providing unique information about the very final moments of massive star evolution. The importance of this pre-SN stage is highlighted by the recently established link between WR stars and Gamma-Ray Bursts (*e.g.*, [38]).

BASIC PARAMETERS OF WR STARS

Population I WR stars are divided into three broad and, probably, evolutionary-successive spectral classes: WN, WC, and WO which are based on appearance of particular emission lines in their spectra (see [19] and references therein). WN stars exhibit the predominance of emission lines of helium and nitrogen, with some presence of carbon, silicon and hydrogen. Spectra of WC stars are dominated by carbon and helium, with an absolute absence of hydrogen. The rare WO class is similar to WC, except that oxygen is seen much more clearly. Each broad class is further sub-divided into subclasses, based on the overall ionization of WR wind. Hence, WN2 and WN11 would define the WN stars of the highest and lowest ionization (effective temperature of the stellar core), respectively. The dense, fast radiatively-driven WR winds efficiently hide all vital information about the basic characteristics (size, temperature, luminosity, chemical composition) of the stellar (hydrostatic) cores. Hence, the zone which may have some resemblance of a main-sequence star photosphere, must be placed in a rather

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arbitrarily chosen region of the outmoving envelope of WR star. This makes direct estimation of the basic parameters difficult, if possible at all.

Membership of some WR stars in open clusters and associations allows to put rather loose limits on the absolute magnitudes [19]: $M_v = -2.4$ to -7.2 for the WN class, with the lowest M_v corresponding to WN2; $M_v = -3.3$ to -4.6 for the WC class; $M_v = -2.8$ for WO. The terminal velocities of the WR winds are, probably, the best established values, as they are measured directly from the UV, optical and IR spectra [43] with a typical accuracy of 10%–20%. They span a broad range: from $v_\infty \sim 500\,\mathrm{km\,s^{-1}}$ for WN11 stars to $v_\infty \sim 4500\,\mathrm{km\,s^{-1}}$ for the WO class. The mass-loss rates come from a wide variety of approaches: from the model-dependent estimates based on radio fluxes (*e.g.*, [23] and the "standard model" calculations (see below)), to the most direct values provided by binary systems with WR components [50]. All the observed and theoretically estimated mass-loss rates are rather extreme, sometimes in excess of $\dot{M} \sim 10^{-5}\,M_\odot\,yr^{-1}$, which is quite sufficient to alter evolution of a massive star. The scarce information about the masses of WR stars comes from binary systems [19]: $M_{\mathrm{WR}} = 2$–$55\,M_\odot$.

As we turn to the temperatures of WR winds and their wind-driving cores, we must call for a help of the so-called "standard model" of WR stars (*e.g.*, [14, 17]). The model solves the transfer equation in the comoving frame subject to a statistical and radiative equilibrium, assuming an expanding, spherically-symmetric, homogeneous WR atmosphere. The stellar radius (R_*) is defined as the inner boundary of the model atmosphere and is located at the Rosseland optical depth of about 20 with the stellar temperature (T_*) defined by the usual Stefan–Boltzmann relation. The "standard model" *does not* solve the momentum equation, so that a density or velocity structure is required. For the supersonic part, the velocity is parameterized with a classical β-type law of the form [22]:

$$v = v_0 + (v_\infty - v_0)(1 - \frac{R_*}{r})^\beta,$$

with $R_* = 1$ and $v_\infty = 1$, $\beta = 1$–3 and $v_0 \leq 0.5 v_\infty$ [31] providing reasonably good fits to the observed WR emission lines in the optical and UV. This [supersonic] velocity field defines the density profile of the expanding wind which is ultimately connected to a hydrostatic density structure at a depth, such that the velocity and velocity gradient match at the interface. The subsonic velocity structure is usually set by corresponding hydrostatic models. This pre-specified wind velocity profile could be the largest deficiency of the "standard model". Indeed, while being able to provide an excellent fit to the UV–IR spectral energy distribution and reasonably well match the shapes of the emission parts of the profiles (Fig. 1, adopted from [34]), the model fails the most critical test, being unable to fit the absorption components of the P Cygni profiles. Can we put any *observational* restrictions on the otherwise unknown wind velocity law? It is a difficult, if not impossible, task for a single WR star. However, in a favourably oriented binary one could be able to perform an analysis of atmospheric eclipses, combining the resonance lines in the UV (large distances from the core) and the subordinate optical transitions (compact and intermediate-size line formation zones – see some examples in [2]). For now, only rough constraints can be placed on the velocity law in the case of the best studied binary V444 Cyg (Fig. 2, adopted from [29]). The traditional β-velocity law provides good fits to some optical lines in V444 Cyg (mainly formed at $r \lesssim a/2$, *i.e.*, at a half-orbital separation). However, there is a systematic and increasing with distance deviation from the β law at $r \lesssim 3/4a$, indicating that a significant and extended wind acceleration may occur at large, $r > 10 R_{\mathrm{WR}}$, distances from the WR core.

What is about the WR radii? Estimates of the *core* radius R_* and temperature T_* require an extrapolation using a $v(r)$ wind expansion law, as well as knowledge of the physics of the optically thick inner WR wind. Both domains remain practically unexplored. However, it is obvious that stars in binaries cannot be larger than the space available for them. Applying this simple principle to Wolf–Rayet binaries in which the constraints are most severe, *i.e.*, to systems with the shortest periods and smallest separations, one may obtain rather strict upper limits for the WR radii, in general $R_{\mathrm{WR}} \ll 10 R_\odot$ [39], in line with the independent estimates obtained by modelling the light curves of eclipsing binary systems with WR components [3]. These alternative values were substantially smaller than the core radii predicted by earlier versions of the "standard model" (*e.g.*, [16, 21]). Incorporation of heavier chemical elements and higher ionization stages in the line lists used in radiation transfer algorithms, as well as a self-consistent treatment of line blanketing in a stellar wind has led to a gradual convergence of the theoretical and observational results [9].

SMALL-SCALE STRUCTURING OF WR WINDS

All *adequately* (good time and spectral coverage, high S/N and spectral resolution) observed WR stars show outwardly-moving, numerous emission "spikes" on the tops of much broader emission profiles. They were interpreted as arising from overdense, small-scale structures embedded into a rapidly accelerating and outmoving

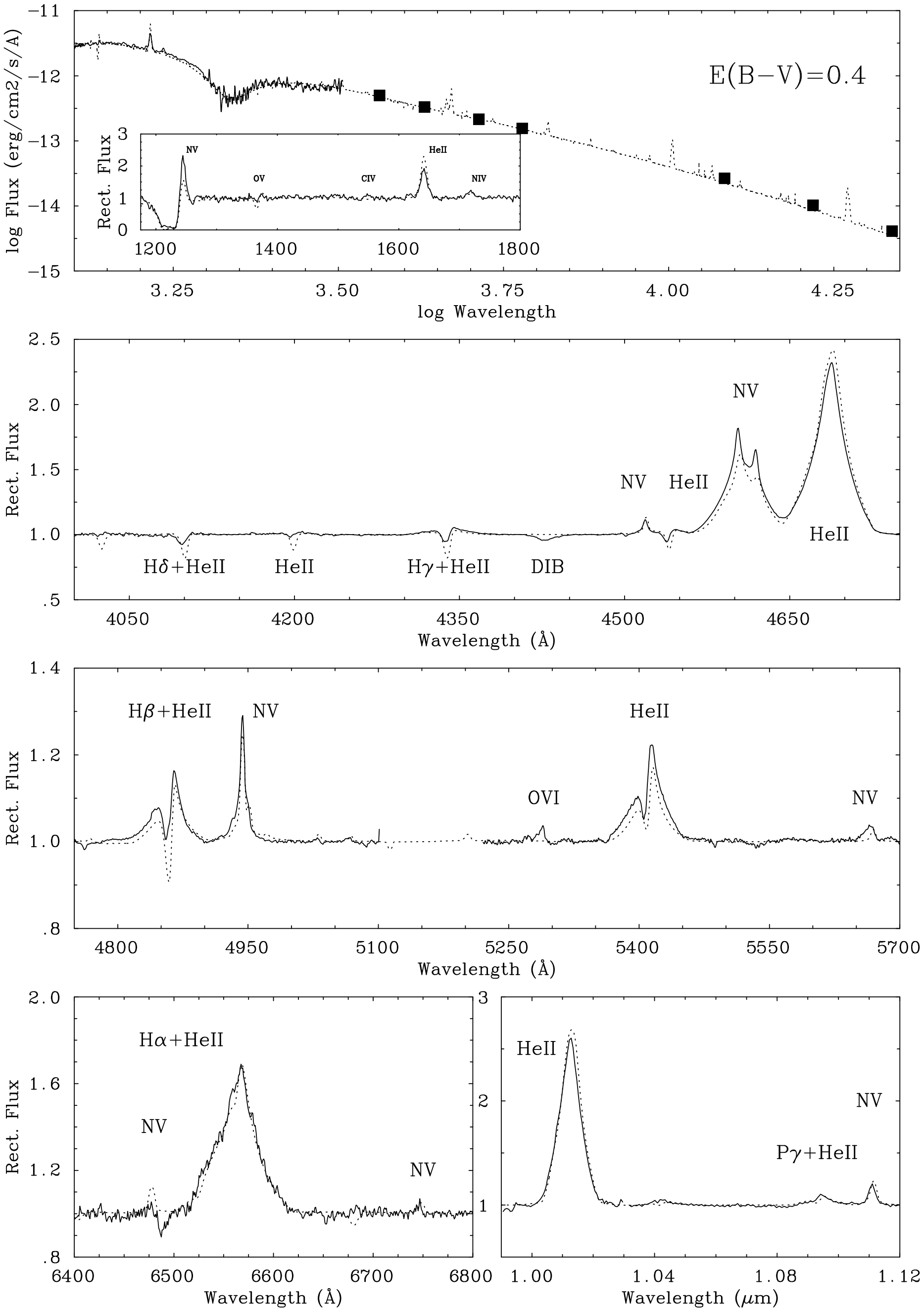

Figure 1. Synthetic spectrum of the resumably single star WR3. Top panel: Spectroscopic comparison between IUE spectrophotometry, *ubvr* photometry and 2MASS JHK photometry for WR3 and synthetic spectrum (dotted) reddened by $E(B-V)=0.4$ mag. Inset is the rectified IUE spectrum, together with the synthetic spectrum (dotted), degraded to the resolution of SWP/LORES and includes the correction for atomic Lyα with $\log N(\mathrm{H\,I})$=21.5 cm^{-2}. Other panels compare the rectified optical and near-IR observations with our synthetic model (dotted)

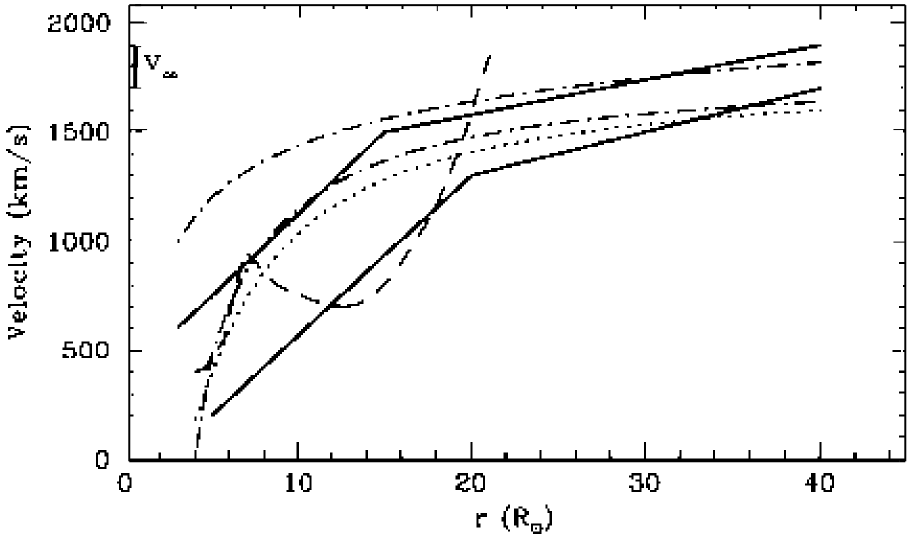

Figure 2. V444 Cyg: thick line – observationally imposed limits on the WR wind velocity law (spectroscopy); dotted line – $\beta = 1.2$ law ([31]; profile fitting); dashed line – [1], light curve solution; dotted-dashed lines – [48], theory

WR wind. So far, the best theoretical explanation relates the rapid rise of these small-scale structures to a specific line-driven instability inherent to any line-driven wind [45]. Numerous direct observations and attempts at their interpretation [24, 46] allow one to draw the following "collective portrait" of the small-scale inhomogeneities in a WR wind [30]. Within a given wind volume, $R_* < r < 10R_*$, there might be $\sim 10^2$ relatively large, $r_{cl} \gtrsim R_\star$, probably optically thick clumps of a total mass of $\gtrsim$ 5% of the ambient wind with a density contrast of $>$ 100. Such density fluctuations are common in numerical simulations [13]. One may assume that roughly the same proportion of large clumps survives to reach much larger distances from the star [47]. The large, massive clumps may accelerate at a much slower pace, thus seemingly defying the wind velocity laws traditionally accepted in modelling. The probable hierarchy of clump sizes results in much more numerous (at least 10^4 [25]), small and optically thin clumps, presumably forming the bulk of the wind. One may only guess about the kinematics of this populace.

Once included in the framework of the "standard WR model", the micro-structuring (clumping) of the WR winds allowed to: (i) produce much better fits of the emission line profiles (especially in the red-shifted electron-scattering wings [15]), (ii) bring theoretical spectral energy distributions closer to the observed infrared and radio fluxes [44]. Probably, the most important issue is the resulting factor 2–5 downward revision of the mass-loss rates in the structured WR winds [15, 18]. This profoundly influences the evolution of massive stars, as the mass loss, along with the initial mass/chemical composition and rotational rate, completely controls evolutionary pathways of massive stars [28]. There is another important consequence of the micro-structured WR wind. Some of WR stars are known to be prodigious dust formers (see below). All the channels of dust formation are deemed to be inoperative unless WR winds are highly structured, thus providing vitally important density enhancements and shielding from the abundant UV photons [4]. Shielding implies a substantial optical depth of the inhomogeneities. Assuming that dust is produced in the optically thick part of the wind (encompassing $\gtrsim 0.05\dot{M}$), one finds a good correspondence with the overall efficiency of the WR dust formation [54].

MACRO-STRUCTURES IN WR WINDS AND ROTATION OF WR STARS

It has recently been demonstrated that, although the mass and mass-loss rate are still the determining factors for evolution in the upper H–R diagram, rotation is an equally important parameter [27]. Although the rotation periods of O stars, predecessors of the WR phase, are relatively well-known, very few measurements have been made for their WR descendants. Based on the width of absorption lines (which are rarely present in WR spectra), a value of $v \sin i \sim 500$ km s^{-1} was claimed for WR138 by [36] and of $v \sin i \sim 150$–200 km s^{-1} for WR3 by [37]. However, for stars with strong winds, one can never be sure that the widths of absorption lines are not dominated by other mechanisms such as turbulence or wind expansion. Indeed, our recent investigation shows that WR3 is likely a single WR star with the turbulence-broadened absorption features arising in a WR wind [34]. But there is an indirect evidence that at least some WR stars may be fast rotators. Currently, favoured model for the long Gamma Ray Bursters is the collapse of a rapidly rotating massive star [26]. On the other hand, model predictions of [27] are that WR stars should be extremely slow rotators ($\ll 50$ km s^{-1}), since most of the angular momentum is carried away by the high mass-loss rate before and during the WR evolutionary phase.

Is there any possibility to gain important information about the rotational velocities of WR stars? The winds of WR stars have been demonstrated to be highly variable. In particular, one type of structure in the wind that may account for some of these variations, Co-rotating Interaction Regions (CIRs), are thought to be closely linked to the rotation of the star. The widely applicable model explains drifting density enhancements as arising from co-rotating interacting regions, *i.e.*, regions of interaction of a slow, "overloaded" wind with a relatively faster "normal" outflow, gradually being brought into the line of sight by stellar rotation [8] in a form of rotating spiral-like structure. These global, large-scale density fluctuations are thought, by consensus, to be driven from a photosphere in the case of OB stars, or are caused by [similar: magnetic field and/or pulsations?] perturbations at the base of WR wind. The initial perturbation rapidly propagates through the wind, being gradually carried by rotation, thus generating a spiral-like structure in the density distribution which leads to a very characteristic, large-scale periodic variability pattern in the emission lines of a WR star. Hence, CIRs may be *the only way* to gain access to rotational periods of WR stars.

In the past decade, two clear cases of this phenomenon have been identified through repeated spectroscopic observations. WR6 ([49]: $P = 3.76$ days) and WR134 ([42]: $P = 2.25$ days) show periodic variations without any indication of a companion. It is generally accepted that the detected periods are the rotation periods of the stars. The periods were found to be independent of distance in the wind, indicating that the CIRs do not suffer from differential rotation but rather enjoy "solid wind" rotation and, therefore, provide a direct measurement of the rotation period of the underlying star. One more example comes from the recently concluded observational campaign on the WN8 star WR123 where we find a dominant (both in the photometric and spectral data) $P \sim 10h$. For typical radii of WR stars, we find equatorial rotation speeds of ~ 40–90 km s^{-1}. Hence, WR stars may be considered as moderately fast rotators.

THE WOLF–RAYET "DUSTARS"

There is one more fascinating feature of the WR mass loss: some carbon-reach WR stars (the ones which belong to the WC spectral class) may form dust. Even though present-epoch dust production output for all Galactic WC stars is $\lesssim 1\%$ of the total Galactic rate [5, 11], the dust-generating WC stars are regarded as outstanding for three main reasons: (i) The absolute rate of dust production is extraordinarily high, reaching $\dot{M} \sim 10^{-6} M_{\odot}$ yr^{-1} [20, 52]. (ii) The dust is formed in a hot, extremely hostile environment, posing a formidable theoretical problem. (iii) In the early (age $\sim$1 Byr) Universe, WR stars could be very common, but unique sources of dust, along with subsequent dust-generating SN events, since WR stars evolve much more rapidly than any lower-mass stars, commonly associated with dust production in the "modern" Universe. It is not clear how much (and what kind of) dust can be produced in a SN explosion [12]. However, it is quite clear that the copious amounts of the carbon-rich dust produced in the WR winds may survive for at least $\sim 10^2$ years [35], thus effectively reaching (and enriching) the ISM.

Two basic processes of dust formation prevail among the WC stars:

(i) "single" channel: constant, sustained formation in single WC stars, only of the coolest (WC9, 10 and some WC8) subtypes. The IR emission excess, arising from re-radiation of stellar UV photons by the hot dust and superposed on an underlying hotter stellar emission component, is in the form of a nearly black-body radiation at $T_d \sim 1000$–1600 K from a shell with inner critical diameter $0.5 \div 1.5 \cdot 10^3 R_\star$ ($0.5 \div 1.5 \cdot 10^4 R_\odot$). Presumably, the winds of hotter single WC stars are too rarefied to form dust at a distance where the UV radiation has dropped sufficiently to allow dust formation to occur. In any case, even in cool WC stars, a smooth wind flow will not form dust; clumping is required for an efficient grain growth [4].

(ii) "binary" channel: episodic formation in binary WC + O systems with eccentric orbits. The key factor here is the compression by wind-wind collision involving H-rich material from the O-star and the C-rich WC wind. This allows dust formation to occur, which is dramatically enhanced at each periastron passage. Among the some seven systems in which episodic dust formation has been detected so far [52], all have (confirmed or suspected) long periods of several years, with no preference for hot- or cool-type WC stars. Presumably, the dust is formed relatively far downstream along the shock interface, where the temperature has fallen sufficiently from the initially extremely high values of 10^{6-7} K. The shock cone wraps around the weaker-wind O-star, so that IR dust emission should arise in a preferred direction far beyond the O-star, as seen from the WR star.

Hot ($T \leq 1500$ K) circumstellar WR dust was only recently spatially resolved around some WC + O binaries [33, 40, 41, 51]. All the above-cited near-IR observations have targeted the hottest dust only. The apparent sub-arcsecond sizes of the barely resolved hot dust regions made next to impossible any direct application of quantitative models. The first mid-IR ($\lambda\lambda$ 8–18 μm) images of the spatially-resolved dust cloud around WR112 [35] provided data on: (a) the temperature profile in the envelope, proving that, as anticipated, the temperature follows a thermal equilibrium profile; (b) the characteristic size and chemical composition of the dust grains, finding amorphous carbon as a main constituent of dust particles of a $\sim 0.5\,\mu$m characteristic size; (c) the absolute rates of dust formation, up to $\dot{M}_{\rm dust} \sim 6 \cdot 10^{-7}\, M_{\odot}\,{\rm yr}^{-1}$. Finishing our mid-IR survey in 2004, we find two more spectacular dust envelopes around Wolf–Rayet binaries WR48a and WR140. The latter example is the most instructive. Indeed, this particular long-period ($P = 7.93$ yr), highly eccentric ($e = 0.881$: [32]) binary serves as a prototype for studies of wind-wind collision phenomena in massive binaries. As an indicator of its importance, the last periastron passage in 2001 was followed by dozens of astronomical facilities, from X-ray to near-IR. Our recent high-quality $\lambda\ 12.3\,\mu$m images show concentric dust arcs around WR140 which can be unequivocally related to the 1993 and 2001 dust formation episodes, thus helping to understand dynamics of dust formation.

The obvious next step is to obtain high-quality mid-IR spatially-resolved spectra of the carbon-based dust clouds. This may answer a broad range of important and fundamental questions: Are there any discernible spectral features which may point to a specific grain material? – different modifications of amorphous carbon-based dust produce distinctly different mid-IR spectra [6, 53]. Are there any traces of polycyclic aromatic hydrocarbons (*e.g.*, [10])? Are there any signs of gradual chemical evolution of dust? How fast is "aging" (annealing? chemical evolution?) of the dust in the presence of intense radiation field? May the wind-embedded shocks change dust properties?

Acknowledgements. The work was supported by the Projects of Distinction Fund of the Western Kentucky University.

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