Episodic Gaseous Outflows and Mass Loss from Red Supergiants

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Received 2021 November 7; revised 2021 December 23; accepted 2021 December 23; published 2022 February 1

Abstract

The red hypergiant VY CMa and the more typical red supergiant (RSG) Betelgeuse provide clear observational evidence for discrete, directed gaseous outflows in their optical and infrared imaging, spectra, and light curves. In the very luminous VY CMa, mass-loss estimates from the infrared-bright knots and clumps not only dominate its measured overall mass loss, but explain it. In the less luminous Betelgeuse, similar mass estimates of its circumstellar condensations show that they contribute significantly to its measured mass-loss rate. We present new measurements for both stars and discuss additional evidence for gaseous ejections in other RSGs. Gaseous outflows are the dominant mechanism for the most luminous RSGs and an important contributor to the more typical RSGs like Betelgeuse. We conclude that gaseous outflows, related to magnetic fields and surface activity, comparable to coronal mass ejections, are a major contributor to mass loss from RSGs and the missing component in discussions of their mass-loss mechanism.

Unified Astronomy Thesaurus concepts: Massive stars (732); Red supergiant stars (1375); Stellar mass loss (1613); Circumstellar matter (241)

1. Introduction

Mass loss from red supergiants (RSGs) has been well known for decades, but the mechanism is not understood. The leading processes have included radiation pressure on dust grains, pulsation, and convection. Pulsation and dust-driven winds have been successful at explaining the mass loss of asymptotic giant branch (AGB) stars, but are not adequate for the less variable RSGs with their very extended, low-density atmospheres. The presence of large-scale asymmetries on the surfaces of RSGs such as Betelgeuse and others lends support to convection as an important source. For examples see Gilliland & Dupree (1996), Monnier et al. (2004), Haubois et al. (2009), and Baron et al. (2014). The recent unexpected dimming of Betelgeuse (Guinan et al. 2019, 2020) corresponded to a remarkable obscuration of its southern hemisphere (Montargès et al. 2021) and an outflow of material from the star (Dupree et al. 2020) observed in UV spectra. Montargès et al. (2021) demonstrate that the fading was due to dust formation related to the gaseous outflow from a convective cell. They estimate a total mass associated with the dusty and gaseous outflow of $7 \times 10^{-8}$ to $3 \times 10^{-7} M_\odot$—significant contribution to Betelgeuse’s overall mass loss.

The history of high-mass-loss events in the luminous, high-mass-losing RSG, VY CMa, is clearly visible in its Hubble Space Telescope (HST) image with numerous knots, clumps, and large extended arcs ejected over several hundred years in different directions from separate regions on the star (Humphreys et al. 2005, 2007, 2019; Jones et al. 2007). Mass estimates of some of the knots and clumps, based on IR imaging and measurements from the Atacama Large Millimeter/submillimeter Array (ALMA), yield minimum masses of $\approx 10^{-2} M_\odot$ (Shenoy et al. 2013; O’Gorman et al. 2015; Gordon et al. 2019). Comparison with its historic light curve from 1800 to the present showed several knots with ejection times that correspond to extended periods of variability and deep minima lasting years (Humphreys et al. 2021). This similar correspondence of massive outflows with unexpected variability and dust formation with Betelgeuse’s brief active period is clear, but on a much larger scale in VY CMa. Near and mid-infrared imaging of Betelgeuse (Kervella et al. 2009, 2011) reveals a circumstellar environment close to the star with arcs and small dusty condensations or knots. Kervella et al. (2018) later suggested that convective cells led to the production of dusty knots and molecular plumes in the north polar region based on ALMA observations. Thus, like VY CMa, Betelgeuse, which is a more typical RSG, also has a history of gaseous outflows from its surface. These two RSGs, in some sense, may represent the range of episodic mass loss—a typical, relatively young RSG and the more extreme, possibly highly evolved, VY CMa.

In this short paper, we review the mass estimates for the discrete ejecta in VY CMa and add an additional infrared-bright knot close to the star. Following similar procedures, we estimate the masses of the small knots close to Betelgeuse. We describe our measurements in the next section. In Section 3, we discuss the resulting mass-loss rates for the two stars, and implications for their mass-loss mechanism. In Section 4, we examine evidence from other RSGs for similar outflows. In the final section we conclude that episodic outflows from large active regions is a primary mechanism for mass loss from RSGs.

2. Measurements and Mass Estimates of Resolved Ejecta

Estimates of the mass in some of the arcs and clumps in VY CMa’s ejecta, based on surface photometry and near-infrared imaging and polarimetry of the SW Clump, yield minimum masses of $\approx 10^{-2} M_\odot$. ALMA submillimeter observations reveal prominent dusty clumps near the star, with the brightest Clump C having a total mass of at least $5 \times 10^{-2} M_\odot$. These measurements are summarized in Table 1.

We have identified an additional bright knot of emission in its 1 $\mu$m HST image (Smith et al. 2001; Humphreys et al.
2007), knot W2, 0°48 NW of the central star (see Figure 1 in Humphreys et al. 2019). Using the same procedure as described in Shenoy et al. (2013) for their analysis of the SW Clump in 2–5 μm images of VY CMa, we find that the W2 knot is also optically thick to scattering. With the same dust parameters, we derive a minimum dust mass of ≈7.1 × 10^{-3} M_☉, compared to ≈5 × 10^{-3} M_☉ for the SW Clump. The difference is primarily due to the smaller angular size of the W2 knot compared to the SW clump. Assuming a gas-to-dust ratio of 200 (Mauron & Josselin 2011), the lower limit to its total mass is ≈3.4 × 10^{-3} M_☉.

The SW clump in VY CMa was also observed in thermal emission in the 10 μm band by Gordon et al. (2019). They found the SW clump was optically thick in emission as well, and derived a minimum dust mass of ≈5 × 10^{-3} M_☉, in very good agreement with the results from the observations of scattered light.

Kervella et al. (2011) presented 7–20 μm diffraction-limited imaging with VISIR of the dust surrounding Betelgeuse. Combining all of their observations, they identified six condensations or knots within 2″ of the star, labeled A–F. They derived surface brightness fluxes for these features at an effective wavelength of λ ≈ 13 μm, which we use to estimate the mass in each of the knots in a manner similar to the analysis of thermal emission from the SW Clump in VY CMa.

Gordon et al. (2019) used the DUSTY code to determine the emission from optically thick dust at the distance of the SW clump from the central star in VY CMa, but this is not necessary for an analysis of the clumps surrounding Betelgeuse. Adopting the same dust parameters as used for VY CMa, we find that, unlike the SW Clump in VY CMa, clumps A–F close to Betelgeuse are all very optically thin. This is easily shown by computing the effective temperature of the dust using the input dust parameters used in DUSTY from Gordon et al.

The distance to Betelgeuse is uncertain, with published distances ranging from 152 pc from the revised Hipparcos parallax (van Leeuwen et al. 2007) to 220 pc (Harper et al. 2017) based on radio positions and proper motions. The results for the masses of the knots, their distances from the star, and ages depend on the adopted distance. In this discussion we show the results for the two most recent results, 168 pc based on asteroseismic and hydrodynamical modeling (Joyce et al. 2020) and 220 pc from Harper et al. (2017). The corresponding luminosity of Betelgeuse is, respectively, 1.26 × 10^5 to 2.16 × 10^5 L☉.

The optical depth is simply

$$
\tau = \frac{S}{B(T)}
$$

where S is the observed surface brightness from Figure 11 in Kervella et al. (2011) at an effective wavelength of 13 μm, and B is the Planck function for the dust temperature at the distance of the relevant knot from the star. This temperature is usually somewhat higher than the blackbody equilibrium temperature of the dust due to differing absorption efficiencies between the wavelengths of the incident radiation from Betelgeuse and the emitted wavelength (see the discussion and Table 2 in Gordon et al. 2019 for an example).

Using the same size distribution and optical parameters for the dust from Gordon et al., we can estimate the column depth of the dust mass in each feature. The effective beam size diameter used by Kervella et al. in their analysis of the knots is 0″38, corresponding to 64 and 84 au at distances of 168 and 220 pc, respectively. Using our estimate of the column depth of the dust mass and the corresponding surface areas, we computed the range in the dust mass for each feature in Table 2 for the two distances. The range in computed masses is due to the combined uncertainties in the fluxes and the dust model parameters. The range in the total dust mass for the six condensations and the total mass (gas + dust) is also summarized. We chose a gas-to-dust ratio of 200 for comparison with the results for Betelgeuse in Montargès et al. (2021). In the following discussion, we adopt total masses of (2.1 ± 0.07) × 10^{-6} M_☉ and (3.6 ± 1.4) × 10^{-6} M_☉, respectively, for the two distances.

Based on high-spatial-resolution visual and near-infrared imaging of Betelgeuse, Montargès et al. (2021) concluded that the recent dimming of Betelgeuse can be interpreted as due to a large obscuration of a part of the stellar disk by dust that condensed not far above the photosphere. Based on the amount of dimming and the size of the obscuration on the disk, their rough estimate of the dust mass necessary to explain the dimming was (0.3–1.3) × 10^{-6} M_☉. The upper end of the range is similar to the dust mass estimates we have derived for the six knots surrounding Betelgeuse. This suggests that if the recent dimming is due to the formation of dust in a mass-loss event, this new outflow or clump will travel out from Betelgeuse over time and resemble the knots or condensations observed in emission in the 7–20 μm regime.
3. Results—the Mass-loss Rates

The mass estimates in Table 1 for VY CMa are for four different knots or clumps with independent measurements. The dusty knots are optically thick in the near and mid-infrared, thus those estimates are lower limits. The estimate of Vlemmings et al. (2017) for Clump C from 178 GHz continuum observations is obviously high with respect to the others. Deleting it, the average mass lost is about 2 \times 10^{-7} M_\odot, somewhat greater than the mass of Jupiter. Adopting the average outflow velocity of the inner knots of 27.5 km s\(^{-1}\) (Humphreys et al. 2021), the kinetic energy of each ejection is of the order of 10^{44} \text{ erg}, equivalent to the Sun’s radiation in a thousand years.

Adopting a minimum mass of 10^{-2} M_\odot for the gaseous outflows associated with the deep minima in VY CMa’s light curve, it shed \approx 7 \times 10^{-2} M_\odot during its active period with seven minima in the early 20th century. During this 20 yr period, from 1925 to 1945, VY CMa’s corresponding mass-loss rate was thus \approx 3 \times 10^{-3} M_\odot yr\(^{-1}\). The corresponding energy expended is a relatively modest one thousandth of the star’s total luminosity. VY CMa’s light curve shows three periods with deep minima separated by about 60 yr, although the onset and end of the late 19th century minimum are uncertain. To get an estimate of its overall mass-loss rate, we assume that over a 100 yr period, VY CMa loses mass at the above rate about 20% of the time and at a quiescent rate of 5 \times 10^{-6} M_\odot yr\(^{-1}\) (O’Gorman et al. 2015). The corresponding net rate is thus 6 \times 10^{-4} M_\odot yr\(^{-1}\), comparable to the observed rates of (4–6) \times 10^{-4} M_\odot yr\(^{-1}\) from several sources (Shenoy et al. 2013; Danchi et al. 1994). For VY CMa, its massive gaseous outflows do not just dominate its current mass loss, they explain it.

The situation is different for Betelgeuse. The total mass in its dusty condensations in Table 2, \((2.1–3.6) \times 10^{-6} M_\odot\), is more than a thousand times less than in the separate knots in VY CMa. To estimate the mass-loss rates from these knots, we need their ages when they were expelled, which depends both on their distance from the star and their outflow velocity. Velocity measurements from clouds of gas in Betelgeuse’s circumstellar environment range from 12 to 18 km s\(^{-1}\) (Bernet et al. 1979; Smith et al. 2009), and Dupree et al. (2020) gives 7 km s\(^{-1}\) for the recent outflow.

These are radial velocities. The total velocity will undoubtedly be higher and yield a lower age. These age estimates also do not take into account possible projection effects, which increase the distance from the star and lead to a somewhat higher age. Depending on their size, these two effects tend to counteract each other. Second-epoch images are necessary to determine the transverse velocity, the direction of the outflows, and their orientation. Pierre Kervella (private communication) reports that additional VISIR images were obtained during the 2019–2020 dimming, which they are currently comparing with the 2010 images. For this discussion, we adopt an outflow velocity of 10 km s\(^{-1}\) and assume that the condensations are in the plane of the sky. Table 3 summarizes their distances in arcseconds and au for the two distances and their estimated ages.

The distances and ages in Table 3 and the spatial distribution of the knots with respect to the star suggest that they divide into two groups, ABC and DEF. At the nearer distance, their respective ages are 73 \pm 8 and 129 \pm 7 yr. With a timescale of 56 \pm 7 yr, and a total mass of \((2.1 \pm 0.7) \times 10^{-6} M_\odot\), the mass-loss rate from the knots is \((3.7 \pm 1.3) \times 10^{-8} M_\odot \text{ yr}^{-1}\). At the greater distance of 220 pc, their average ages are 96 \pm 10 and 168 \pm 9 yr. Thus over a timescale of 72 \pm 9.5 yr, they shed a mass of \((3.6 \pm 1.2) \times 10^{-6} M_\odot\), for a comparable rate of \((5 \pm 1.8) \times 10^{-8} M_\odot \text{ yr}^{-1}\). The two distances yield essentially the same mass-loss rates within their errors.

The published mass-loss rates for Betelgeuse range from a low of \((2 \times 10^{-7} M_\odot \text{ yr}^{-1})\) up to \((2 \times 10^{-6} M_\odot \text{ yr}^{-1})\) (De Beck et al. 2010; Dolan et al. 2016). With the lower rate, the gaseous outflows contribute \approx 20% over these timescales, but with the higher number the contribution is only a few percent. These numbers are consistent with the estimate of Montargès et al. (2021) of the contribution from the recent outflow to the annual mass loss from Betelgeuse.

To extend the timescale, we can add the small condensations close to the star, labeled 1, 2, and 3 in Kervella et al. (2011). They are at about the same distance from the star, 0"5. With the same outflow velocity, they were all ejected at about the same time, approximately 42–55 yr ago. Assuming the average mass for each knot, with the additional time span and the increase in total mass, the resulting mass-loss rates are essentially the same as those quoted above.

Although examination of Betelgeuse’s historic light curve did not reveal any deep minima comparable to the 1990–2020 event (Montargès et al. 2021), we compared the corresponding calendar dates for the outflows with the AAVSO visual light curve for Betelgeuse. The light curve from 1900 to the present shows a broad dip circa 1940 (1938–42) and three minima in the mid 1940s1 with minimum magnitudes of \approx -1.5 mag. Either of these could correspond to the ejection age of knots ABC at the nearer distance. At the larger distance, knots ABC would correspond to the early 20th century when the observations are sparse. Knots DEF were apparently ejected before 1900, circa 1880 or 1840. The historic light curve from Baxendale (1840–1884)2 does not show any obvious minima or significant changes in its visual magnitude near these dates, although there are significant gaps in the observations. We also find no apparent features in the light curve that would correspond to the innermost condensations, knots 1, 2, and 3. The possible outburst dates, however, could be uncertain by several years due to the assumed outflow velocity and the unknown projection. Furthermore, the outflows may have been out of our direct line of sight or in a direction that obscured a significant fraction of the star.

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1 Measured relative to the date of the observations, 2010.
2 The historic light curves from Herschel, Argelander, and Baxendale were kindly provided by Tom Calderwood of the AAVSO.
The large gaseous outflows in VY CMa explain its high mass-loss rate, while for the younger and lower-mass Betelgeuse, the contribution is less certain with its overall mass-loss rate varying by a factor of 10. But assuming that the episodic outflows are also contributing significantly to Betelgeuse’s overall mass-loss history.

These relatively massive outflows or ejections, presumably from the large asymmetries or convective cells observed on the surfaces of RSGs, imply the existence of strong magnetic fields. Measurements of circular polarization in SiO, H_2O, and OH and Zeeman splitting of maser emission from the envelope of luminous cool stars have been interpreted as indications of magnetic fields in their winds and ejecta. Vlemmings et al. (2002) measured the circular polarization of H_2O maser emission in several luminous, cool stars, including VY CMa, for which they derive a field strength of 200 mG at a distance of 220 au from the star. Combining estimates of magnetic field strength from OH, H_2O, and SiO maser emission, and extrapolating the field strength back to the photosphere of the star, we estimate a \( \approx 500 \) G field assuming a \( 1/\rho^2 \) solar-type dependence (Figure 15 in Vlemmings et al. 2002). Recently Shimaga et al. (2017) directly measured the Zeeman effect in the SiO \( \nu = 0, J = 1-0 \) transition in the envelope of VY CMa, and derived field strengths in the emitting region of anywhere from 10 G (lower limit) to 500 G (upper limit). They conclude that VY CMa must have a very strong magnetic field in its mass-loss wind. Furthermore, continuum images with ALMA (Vlemmings et al. 2017) reveal polarized dust emission from magnetically aligned grains on subarcsecond scales close to the star, consistent with a magnetic field strength of 1–3 G in the inner wind.

It is tempting to interpret the large, distinct mass-loss events seen in VY CMa as a scaled-up version of large eruptive events (coronal mass ejections, CMEs) in the Sun. In their analysis of the global energetics of recent solar CME events, Emslie et al. (2012) find that the available magnetic energy is sufficient to power the CMEs. The largest documented solar CME was the Carrington event in 1859, with a total kinetic energy of \( KE \approx 10^{33} \) erg (Cliver & Dietrich 2013). This event would have required field strengths of \( B > 200 \) G in a volume diameter just above the surface of \( D \approx 0.1 R_* \). Scaling to VY CMa, the expected kinetic energy of the clumps or knots is \( KE \geq 10^{24} \) erg, which would require a field strength of \( B \geq 1000 \) G in a volume of diameter \( \sim 1 \) au (0.1 \( R_{\text{eff}} \)) at the surface, comparable to our estimates.

Comparable magnetic fields have been measured in the ejecta of other RSGs with maser emission such as VX Sgr, NML Cyg, and S Per (Vlemmings et al. 2002, 2005) as discussed in the next section. Betelgeuse is not a maser source, but Aurière et al. (2010) and Mathias et al. (2018) report circular polarization in the photospheric absorption lines due to a longitudinal magnetic field of \( \approx 1 \) G, which may be associated with the giant convective cells on its surface. Tessore et al. (2017) detect similar Zeeman signatures in the RSGs CE Tau and \( \mu \) Cep with comparable surface fields also at the 1 G level.

We would expect X-ray emission to likewise be associated with the magnetic activity and the large outflow. However, VY CMa was not detected in XMM-Newton observations (Montez et al. 2015) with an upper limit to the average surface magnetic field strength \( fB \lesssim 2 \times 10^{-3} \) G where \( f \) is the filling factor. These observations were obtained in 2012, two decades after VY CMa’s most recent active period in \( \sim 1985 \), when it may have been in a state of lower magnetic activity. Interestingly, Betelgeuse’s outflow and dimming were also not measured in X rays (Kashyap et al. 2020) with the Chandra X-ray telescope. In both cases the X-ray observations were obtained after the active period.

4. Evidence for Gaseous Outflows from other RSGs

Without direct observation of a gaseous outflow as in Betelgeuse or a history of episodic mass-loss events as observed in VY CMa, it will be difficult to confidently identify outflows separate from other variability common to RSGs. A frequent record of photometry and spectroscopy perhaps accompanied by direct imaging, when possible, is needed. But such a record is lacking for most RSGs. In this section we briefly discuss a few promising stars with high mass-loss rates, dusty environments, and resolved circumstellar ejecta.

The luminous OH/IR stars NML Cyg, S Per, and VX Sgr are obvious candidates. Like VY CMa, they have measurable magnetic fields in their ejecta (Vlemmings et al. 2002) from the polarization of their water masers that when extrapolated back to their surfaces also imply surface fields of a few hundred Gauss. The highly variable, high-luminosity VX Sgr has a measured dipole field from the polarization of the H_2O masers, implying a surface field of the order of 1000 G (Vlemmings et al. 2005). All three of these high-luminosity RSGs have extended circumstellar ejecta in their visual and red HST images (Schuster et al. 2006), and measured mass-loss rates from \( 5 \times 10^{-5} \) to \( >10^{-4} M_\odot \) yr\(^{-1} \) (Shenoy et al. 2016; Gordon et al. 2018).

In many respects NML Cyg most closely resembles VY CMa. Singh et al. (2021) and Andrews et al. (2021) have recently identified two gaseous outflows in its molecular emission spectrum at millimeter wavelengths. The outflows are blue and redshifted relative to the star’s systemic velocity and appear to be aligned with the tips of its small bean- or half-moon-shaped image (Schuster et al. 2006). They very likely trace sporadic mass-loss events. In addition, NML Cyg has 17 different molecules including carbon species identified in its 1 mm spectrum in common with VY CMa. NML Cyg’s peculiar morphology is attributed to its environment. It is embedded in the Cygnus X superbubble and subject to the intense UV radiation from the numerous hot stars in nearby Cyg OB2 (Schuster et al. 2006, 2009). Otherwise we suspect that NML Cyg would be accompanied by complex circumstellar ejecta similar to VY CMa.

It is not known whether S Per and VX Sgr have experienced episodic outflows. Both show extended ejecta but without obvious substructure (Schuster et al. 2006), although recent 3–13 \( \mu \)m images of VX Sgr (Chiavassa et al. 2021) reveal a complex surface morphology with possible surface asymmetries. Another clue is anomalous large variations or deep minima in their light curves similar to VY CMa in the early 20th century or smaller episodes as in Betelgeuse. For example, S Per is a known semiregular variable typically with visual light variability of at most \( \pm 1 \) mag and a primary period of about 800 days (Kiss et al. 2006). Its light curve from \( \sim 1900 \) to 2020 shows a few isolated deep minima, but the extended period of about 10 years (1990–2000), with deep minima of about four magnitudes, is exceptional and is reminiscent of VY CMa’s variability in the early 20th century. Afterwards, S Per was about half a magnitude fainter, suggesting that this period
of increased instability was followed by dust formation. It is tempting to speculate that, as in VY CMa, S Per had a period of increased mass loss, possibly due to surface activity and outflows, although enhanced pulsation is possible.

VX Sgr is a semiregular variable that at times behaves like a fundamental-mode pulsator (a Mira variable) with deep minima, fading by 5–6 mag. Although some authors suggest VX Sgr may be a “super AGB” star (Tabernero et al. 2021) based on its Mira-like variability, its fundamental-mode pulsation does not rule out a core-burning supergiant (Heger et al. 1997). Current distance estimates ranging from 1.5–1.7 kpc due to possible association with Sgr OB1 and the Sgr spiral arm (Humphreys 1975) to 1.3–1.4 kpc (Tabernero et al. 2021) indicate a luminosity well above the AGB limit, even taking into account the possibility that a few AGB stars occasionally have luminosities above the AGB limit (García-Hernández et al. 2009). In this paper we treat VX Sgr as an RSG.

Several other high-luminosity RSGs are high-mass-losing, dusty, and known maser sources, such as AH Sco and MY Cep, and are candidates for active surfaces and gaseous outflows. For example, surface structure has been reported on AH Sco (Wittkowski et al. 2021), and an atmospheric analysis reveals extended molecular layers that need to be elevated above the predictions of the models (Arroyo-Torres et al. 2013).

More typical, less luminous RSGs, like Betelgeuse, with smaller and shorter mass-loss episodes or gaseous outflows would be harder to identify or less likely to be identified unless the star was being frequently monitored. However, high-resolution imaging and spectroscopy of RSGs is confirming large surface irregularities in more stars. Furthermore, clumpy winds observed in RSGs ranging from less luminous members such as α Sco (Oihnaka 2014) to μ Cep (Montargès et al. 2019), one of the visually brightest RSGs, may be the consequence of surface activity not manifested in massive outflows.

5. The Mass-loss Mechanism for Red Supergiants

There are problems and complications with the three leading mass-loss mechanisms for the RSGs: radiation pressure on dust grains, pulsation, and convection. Dust-driven mass loss, which works well for the AGB stars (van Loon et al. 2006; Hofner 2008), would initially seem the most likely for the dusty RSGs. But the radiation-dependent models depend on a direct relation between the mass-loss rate and the intrinsic luminosity of the star, which is not confirmed by observations (Mauron & Josselin 2011). Although there is a clear dependence of mass-loss rate on luminosity, radiation pressure on grains does not explain the scatter in the observations. In our recent discussion of mass loss from RSGs (Humphreys et al. 2020), we also noted the scatter and recommended that the relation is better represented by a broad band or curve than a tight linear relation.

Most RSGs are known variables, so it is reasonable to suspect that radial pulsation would play a role by expanding the outer layers and depositing material at radii where dust can condense, similar to the highly variable AGB stars. However, this is less efficient for the already very extended low-density atmospheres of the RSGs. Given the prevalence of convective cells now observed on several RSGs, a combination of pulsation and convective activity may explain the mass loss from the RSGs. For example, the recent gaseous outflow from Betelgeuse and dimming apparently corresponded to the maximum photospheric outflow velocity during its pulsation cycle of 400 days (Dupree et al. 2020; Granzer et al. 2021; Montargès et al. 2021).

In-depth studies of the atmospheres of two luminous RSGs, AH Sco (Arroyo-Torres et al. 2013, 2015) and V602 Car (HD 97671; Climent et al. 2020), however, show that pulsation and convection alone cannot explain the elevation of material to the molecular and dust formation zones. Note that AH Sco is a known source of maser emission, and near-infrared imaging of V602 Car reveals large convective regions in its extended atmosphere.

An additional mass-loss mechanism is required. We suggest that the missing component is episodic high-mass-loss outflows very likely driven by large-scale convection together with magnetic fields comparable to CMEs. We have shown here that these gaseous outflows explain the very high mass-loss rate in VY CMa and contribute to the mass loss from the less luminous Betelgeuse.

Admittedly, we only have two confirmed examples—three with NML Cyg—but we emphasize the similarity of VY CMa to the other RSGs with remarkably high mass-loss rates. In addition to mass-loss rates $\sim 10^{-4} M_\odot$ yr$^{-1}$, many of the most luminous RSGs have several shared characteristics including late spectral types (M4–M7), circumstellar ejecta, maser emission, plus measurable magnetic fields in several. Outflow events in the more typical, less luminous RSGs may be more difficult to detect and may contribute less to the total mass-loss rate. Thus the presence or lack of outflows may explain the observed spread in the relation between luminosity and mass-loss rate. Furthermore, if we remove the known maser sources and stars with high mass-loss rate from Figure 12C in Humphreys et al. (2020), the relation is more linear. This may be circumstantial, but is suggestive that an additional mass-loss method is important for these RSGs.

We therefore suggest that magnetic fields and surface activity resulting in massive gaseous outflows explain the high mass-loss rates for these exceptional RSGs. Gaseous outflows are the dominant mechanism for the most luminous RSGs and a contributor to the mass loss of the more typical RSGs like Betelgeuse.

This work was supported by NASA through grant GO–15076 (P.I. R. Humphreys) from the Space Telescope Science Institute. We also acknowledge use of the AAVSO visual data light curve for Betelgeuse from 1900 to the present, and thank Tom Calderwood, via private communication to Andrea Dupree, for the early data from Herschel, Argelander, and Baxendell. We also thank Nicolas Mauron and Pierre Kervella for useful comments.

Facilities: STIS, AAVSO.

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3 Gaia parallaxes range from 0.787 ± 0.238 mas (DR2) to 0.046 ± 0.187 mas (DR3).
