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The Metallicity Dependence of the Mass Loss of Early-Type Massive Stars

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Abstract. We report on a comprehensive study of the wind properties of 115 O- and early B-type stars in the Galaxy and the Large Magellanic Clouds. This work is part of the VLT/FLAMES Survey of Massive Stars. The data is used to construct the empirical dependence of the mass-loss in stellar winds on the metal content of their atmospheres. The metal content of early-type stars in the Magellanic Clouds is discussed. Assuming a power-law dependence of mass loss on metal content, $\dot{M} \propto Z^m$, we find $m = 0.83 \pm 0.16$ from an analysis of the wind momentum luminosity relation (Mokiem *et al.* 2007b). This result is in good agreement with the prediction $m = 0.69 \pm 0.10$ by Vink *et al.* (2001). Though the scaling agrees, the absolute empirical value of mass loss is found to be a factor of two higher than predictions. This may be explained by a modest amount of clumping in the outflows of the objects studied.

Keywords. techniques: spectroscopic – stars: atmospheres – stars: early-type – stars: mass loss – galaxies: abundances

1. Introduction

One of the fundamental aims of the *VLT/FLAMES Survey of Massive Stars* (Evans *et al.* 2005, 2006) is to empirically determine the relation between the mass loss rate of early-type massive stars as a result of radiation pressure on spectral lines and their surface chemical composition. The *Fibre Large Array Multi-Element Spectrograph* (FLAMES), the first wide-field, multi-object spectrograph instrument on an 8-m class telescope allowed to collect an unprecedented number of (over) 800 high-quality spectra of stars in the Galaxy and Magellanic Clouds in only ~100 hours of *Very Large Telescope* (VLT) time. A total of seven clusters was observed. For the main sequence objects the wind strengths are a strong function of spectral type, therefore only the sub-sample of O and early-B stars can be used to determine the relation between mass loss $\dot{M}$ and metal content Z. The young cluster N11 in the Large Magellanic Cloud (LMC) and NGC 346 in the Small Magellanic Cloud (SMC) are particularly rich in these objects (see Fig. 1).

Here we present an overview of the main results of this part of the FLAMES project. Specifically, we discuss the chemical composition of the Magellanic Clouds (Sect. 2) and the modified wind momentum diagram from which the $\dot{M}(Z)$ relation is derived (Sect. 3). We end with an outlook on extending the mass loss vs. metallicity relation towards metallicities below that of the SMC.

2. The metallicity of the Magellanic Clouds

The winds of massive stars are driven by spectral lines of heavy elements, in particular iron. Unfortunately, the optical spectra of O stars show few features of these species. B stars, however, are relatively rich in absorption lines due to carbon, nitrogen, oxygen,

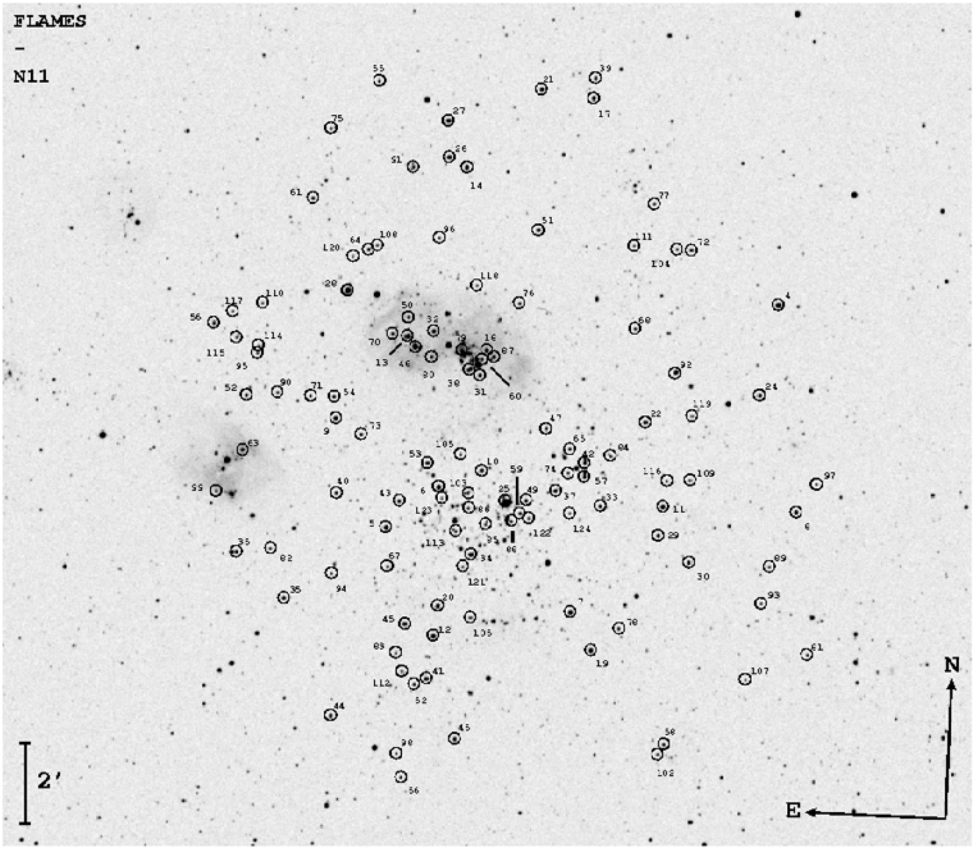

Figure 1. V-band wide field image of FLAMES targets in N11 in the LMC. Our observations sample the central associations of LH9 (south of center) and LH10 (north of center), and the surrounding regions. Stellar parameters of 22 O and early-B stars have been determined using an automated fitting method. Image from Evans *et al.* (2006).

magnesium, aluminum, silicon and sulphur. Iron lines are also present though these are intrinsically quite weak (especially so in the SMC; Rolleston *et al.* 2003). The present-day composition for over 100 slowly-rotating early-B stars in the LMC and SMC was studied by Hunter *et al.* (2007) and Trundle *et al.* (2007) using the TLUSTY model atmosphere code. In Table 1 the derived abundances are given, supplemented with results for Al and S from the literature.

Trundle *et al.* (2007) determine a mean relative to solar iron abundance for 13 stars of their sample in NGC 2004 in the LMC of $\Delta[\mathrm{Fe/H}] = -0.29 \pm 0.13$, in good agreement with the depletions of O, Mg and S. Notice that C and N are significantly underabundant in the clouds. We adopt $\Delta[Z/\mathrm{H}] = -0.3 \pm 0.1$ for the LMC, but note that the carbon and nitrogen depletion may have a small effect on the wind strengths of the hottest stars where these elements (mainly C) are a significant contributor to the line force.

In the SMC the mean relative to solar of the α elements (O, Mg, Si) is $\Delta[\mathrm{Fe/H}] = -0.7 \pm 0.1$. The differential result of Al is in good agreement with this value. The iron abundance $\Delta[\mathrm{Fe/H}] = -0.57 \pm 0.16$ is somewhat higher, but is in agreement within the uncertainties. Studies of AFGK supergiants, which have more and stronger metal lines, tend to yield an iron abundance that is in good agreement with this value (Venn 1999).

Table 1. Present-day chemical composition of the LMC and SMC from B stars. The solar abundances of Asplund *et al.* (2005) are given for reference. References: Hunter *et al.* (2007), Trundle *et al.* (2007), Rolleston *et al.* (2002), Rolleston *et al.* (2003). The latter two references pertain to aluminum and sulfur and reflect LTE results. From Mokiem *et al.* (2007b).

Element	Solar	LMC		SMC	
		$12 + \log X/\mathrm{H}$	$\Delta[X/\mathrm{H}]$	$12 + \log X/\mathrm{H}$	$\Delta[X/\mathrm{H}]$
C	8.39	7.73	−0.66	7.37	−1.02
N	7.78	6.88	−0.90	6.50	−1.28
O	8.66	8.35	−0.31	7.98	−0.68
Mg	7.53	7.06	−0.47	6.72	−0.81
Al	6.37	...	...	5.43	−0.72
Si	7.51	7.19	−0.32	6.79	−0.72
S	7.14	...	...	6.44	−0.42
Fe	7.45	7.23	−0.29	6.93	−0.57

We adopt $\Delta[Z/\mathrm{H}] = -0.7 \pm 0.1$, but will point out the effect of a higher SMC metal content on the mass loss vs. metallicity relation in Sect. 3.

3. Mass loss as a function of environment

The mass loss vs. metallicity relation presented in the paper is based on 115 objects. As the metallicity differences in the three galaxies considered are modest, it is important that the photospheric and wind parameters of this sample are derived in as homogeneous a way as is possible. To cope with the large dataset provided by the FLAMES survey, to improve the objectivity of the analysis, and to strive towards a homogeneous analysis we have developed an automated fitting method of spectral lines based on genetic algorithms (Mokiem *et al.* 2005). The method uses synthetic line profiles generated by FASTWIND (Puls *et al.* 2005), was successfully tested using well studied Galactic objects (Herrero *et al.* 2002; Mokiem *et al.* 2005) and applied to FLAMES LMC (Mokiem *et al.* 2006) and SMC (Mokiem *et al.* 2007a) targets. An important advantage of our approach is that the derived uncertainties in the model parameters reflect possible degeneracies (in combinations of parameters). Moreover, if the mass loss rate is so low that its prime diagnostic (in our case Hα) is no longer significantly affected by wind emission the method will signal this by being unable to quantify a lower limit to $\dot{M}$.

Though sizeable, the total number of objects does not allow to establish the relation between mass loss and chemical composition on the basis of a comparison of "identical" (except for Z) objects in the Galaxy, LMC and SMC. Actually, this would not even be an appealing approach given the possibility that stars in different parts of the Hertzsprung-Russell diagram and/or of disparate mass may not obey the same $\dot{M}(Z)$. At present the only way to get more insight in the universality of the mass loss-metallicity relation is to turn to predictions of radiation-driven wind theory. A powerful way to proceed is through the use of the *modified wind momentum - luminosity relation*, (WLR; e.g. Kudritzki & Puls 2000)

$$\log D_{\mathrm{mom}} \equiv \log(\dot{M} v_{\infty} \sqrt{R}) \simeq x \log(L/L_{\odot}) + \log D_{\circ}, \tag{3.1}$$

where the slope x and the constant $D_{\circ}$ may vary as a function of spectral type and metal content (see e.g. Puls *et al.* 2000). The WLR expresses that the mechanical momentum of the stellar wind (the product of mass loss $\dot{M}$ and terminal flow velocity v_{∞}) is primarily a function of photon momentum (the ratio of the luminosity L and the speed of light c).

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The uniqueness of the WLR for specific ranges in spectral type and metallicity has been confirmed by e.g. Vink *et al.* (2000).

Assuming that mass loss and terminal velocity are power laws of metallicity, i.e.

$$\dot{M} \propto Z^m \qquad \text{and} \qquad v_\infty \propto Z^n, \tag{3.2}$$

it follows that

$$(m+n) = \Delta \log D_{\rm mom} / \Delta \log Z. \tag{3.3}$$

It is found that for O and early-B stars the slope x is quite similar, though not identical, for the Galaxy and Magellanic Clouds. Because of the slightly varying slopes, a fixed luminosity is picked at which the respective WLRs are compared. We have used $L = 10^{5.75}\,L_\odot$. For the dependence of v_∞ on metallicity we adopt the theoretical value $n = 0.13$ (Leitherer *et al.* 1992).

The Galactic WLR consists of 49 objects, ranging in spectral type from O2 to B1 and includes dwarfs, giants and supergiants, of which 24 percent was analyzed with the automated method. The properties of the bulk of this sample are collected from the literature. In doing this, we restricted ourselves to using results based on state-of-the-art unified non-LTE line-blanketed model atmospheres only (Hillier & Miller 1998; Puls *et al.* 2005). Stars for which only upper limits to the mass loss rate could be determined were discarded. This was done also for the LMC and SMC case. The LMC sample has 38 objects, of which 58 percent is analyzed using the automated method. Coverage of spectral classes is similar as for the Galactic sample. The 22 targets observed in the FLAMES program have more than doubled the statistics of LMC stars (of these types). It is this improvement in numbers that has allowed us to construct the first robust WLR for this galaxy. Anticipating the outcome, the FLAMES results have established for the first time that the wind strengths of LMC stars are intermediate between those of Galactic and SMC stars. Finally, 28 objects in the SMC were analyzed. Again, coverage of spectral classes was similar as for the Galactic case. For this galaxy 43 percent of the objects were modeled using the automated method. For further details we refer to Mokiem *et al.* (2007b).

The three empirical WLRs are presented in Fig. 2. The top, middle and bottom relations (solid lines), respectively, correspond to Galactic, LMC and SMC observations. One sigma confidence intervals are shown as gray areas. A linear regression using the three $D_{\rm mom}$ values at $L = 10^{5.75}\,L_\odot$, accounting for both the errors in $D_{\rm mom}$ and Z, yields

$$\dot{M}_{\rm empirical} \propto Z^{0.83 \pm 0.16}. \tag{3.4}$$

How does this result compare with theoretical expectations? The dashed lines in Fig. 2 show predictions by Vink *et al.* (2000, 2001). The top, middle and bottom relations, respectively, correspond to Galactic, LMC and SMC predictions. They find

$$\dot{M}_{\rm predicted} \propto Z^{0.69 \pm 0.10}. \tag{3.5}$$

The quoted error in this prediction accounts for random errors in the Monte Carlo method that is applied (see de Koter *et al.* 1997). An independent study by Krtička (2006) confirms the result. We conclude that the power-law behavior of the empirical and predicted $\dot{M}(Z)$ agree within these random error limits. Systematic uncertainties are not accounted for in the value of m. To illustrate this: if the metal content of the SMC is higher than adopted (see Sect. 2), say, $\Delta[Z/{\rm H}] = -0.5 \pm 0.1$, both the empirical and theoretical dependence would be stronger: $m \simeq 1.1$.

Notice that the theoretical results underpredict the empirical results by some 0.24–0.35 dex in the logarithm of $D_{\rm mom}$. This corresponds to about a factor of two difference in

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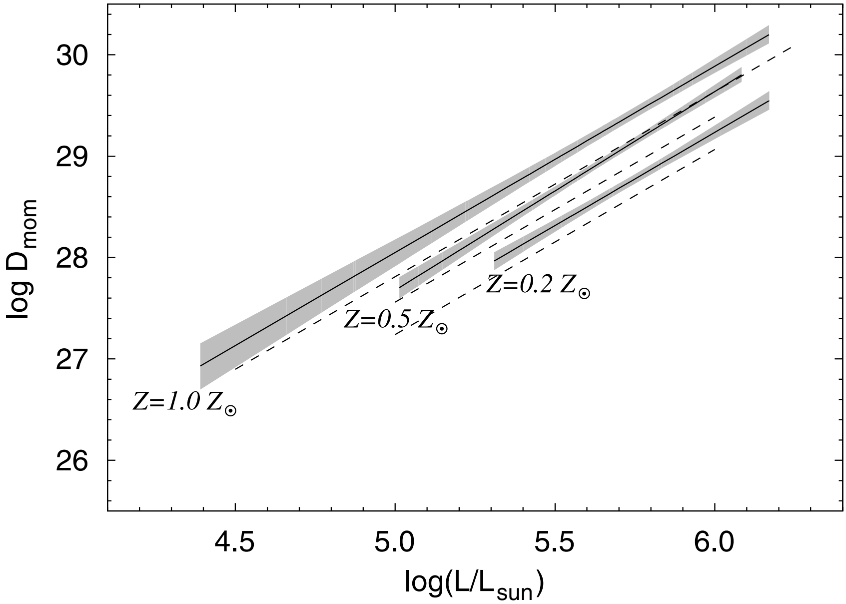

Figure 2. Comparison of the observed wind momentum – luminosity relations for O and early-B stars (solid lines) with the predicted relations of Vink *et al.* (2000, 2001) (dotted lines). Top, middle and bottom lines of each line style, respectively, correspond to Galactic, LMC, and SMC observed and predicted WLRs. One sigma confidence intervals for the empirical relations are shown as gray areas. Among others, this figure for the first time shows that the wind strengths of LMC stars are intermediate between those of Galactic and SMC stars. From Mokiem *et al.* (2007b).

the mass loss rate. The physical reason for this offset is not known, however, if the stellar outflows are clumped on small spatial scales in the region of Hα line formation this discrepancy may be resolved. Owing to the fact that Hα (the most important wind diagnostic in the optical) is the result of recombination, the strength of this line scales with the square of the density. A local overdensity in clumps thus overcompensates the presence of void interclump regions. Introducing the clumping factor $f_{\rm cl} =< \rho^2 > / < \rho >^2 \geqslant 1$ where angle brackets denote (temporal) average values (e.g. Puls *et al.* 2006), the mass loss required to fit the Hα profile in case of a structured wind will be less than that assuming a smooth ($f_{\rm cl} = 1$) outflow. It follows that $\dot{M}(\text{clumped}) = \dot{M}(\text{smooth wind})/\sqrt{f_{\rm cl}}$. Given the size of the offset only a modest clumping of $f_{\rm cl} \sim 3$–5 is required to bring the empirical and predicted WLR in agreement. Notice that this assumes that clumping has no significant effect on the predictions of mass loss. Notice also that if the properties of small scale structure are independent of metallicity, *the* $\dot{M}(Z)$ *scaling is unaffected by the presence of clumping, regardless the absolute value of the clumping factor.*

4. Outlook

The WLR in the SMC is derived from objects more luminous than $10^{5.2} L_\odot$ (see Fig. 2). Therefore, the mass loss vs. metallicity scaling is strictly speaking only valid for such bright objects, objects that show strong winds. For intrinsically dimmer stars, having weaker winds, the WLR relation is being discussed (see e.g. Fullerton *et al.* 2006; Mokiem *et al.* 2007b). Also, $\dot{M}(Z)$ has only been derived for metallicities down to 1/5th the solar value. Though predictions claim a constant power-law for all Z values between

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1/30th and 3 $Z_\odot$ (Vink *et al.* 2001), this remains to be verified. In the foreseeable future the only possibility of studying stars in environments with significantly lower metallicity than the SMC is the young massive population of Local Group dwarf galaxies such as GR8, Leo A, Sextans A, WLM, IC1613, and perhaps IZw18. These systems have metallicities between 1/10th and 1/35th of solar. So far, focussed spectroscopic attempts to characterize the massive star population have been limited. The studies that have addressed blue objects typically focus on supergiants of spectral type mid-B to A (e.g. Kaufer *et al.* 2004) with the aim to establish abundances and use them as distance indicators, though observations of earlier spectral types including late-O stars are becoming feasible (Bresolin *et al.* 2006, 2007). The situation may improve once the *X-Shooter* spectrograph is installed on the VLT. Anticipating that X-Shooter will deliver the gains in efficiency that it expects, high-quality spectroscopic observations of mid-O stars should be possible. This will allow for a first confrontation between observations and theory at $Z \leqslant 1/5 Z_\odot$.

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Discussion

WALBORN: I'm concerned that there are three categories of O stars with 'weak winds' that are sometimes not clearly distinguished in analytical studies: 1) SMC stars with weak wind lines due to metal deficiency; 2) Very young O stars that may be on or near the ZAMS and subluminous, with weak wind lines for their spectral types (my review at STScI May 2006 symposium, still astro-ph/0701573 only); 3) Stars with normal wind line

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strengths for their spectral types, for which current model analyses derive anomalously low mass-loss rates, e.g. 10 Lac.

de Koter: Your group 2 and 3 refer to the 'weak wind problem'. I didn't discuss it today, but its good that you mention it. Your group 1 stars have weaker winds, as I've quantified today. They can be understood in the framework of radiation driven wind theory, as I've shown. Concerning your group 2 and 3 stars I think there are two broad avenues to search for an explanation: a) their winds are really weaker, or b) we miss some understanding of the diagnostics used to determine mass loss, but in reality their winds aren't as weak as they seem. Concerning the latter possibility, a recent paper by Oskinova *et al.* (2007, *A&A* 476, 1331) makes the point that porosity effects may lead to underestimating the mass loss when using ultraviolet resonance lines. A thing that I'm always worried about is that the discontinuity between "weak winds" and "strong winds" is at about the point where Hα looses it sensitivity (for weaker winds one has to rely on ultraviolet lines only). Mokiem *et al.*, using their genetic algorithm method did manage to derive the mass loss for three stars in the "weak wind" regime using Hα, ζ Oph, Cyg OB2 #2, and HD 217086. Interestingly, they did recover values that seem consistent with theory.

Kudritzki: I guess the Fe abundances that you showed are from the optical spectra from your O and B stars. They must be very uncertain, because you have only a very few Fe lines in those optical spectra. I also wonder whether these are based on NLTE calculations.

de Koter: In the context of the FLAMES project, Trundle *et al.* (2007, *A&A*, 471, 625) determined the Fe abundance of B stars in the LMC and SMC. I do agree with you that the Fe abundance, more in general the SMC metallicity, is a very important quantity. Actually, the SMC metallicity might be the largest potential source of systematic error in the power-law of the empirical $\dot{M}(Z)$ dependence. Carrie, do you want to comment on Rolf's question?

Trundle: Only few iron lines are present in the optical spectra of B stars, the best ones being Fe III λ4419 and 4430. For the LMC we used these line to derive an abundance for 13 targets. For our SMC stars Fe III λ4430 is too weak. We used the 4419 line to derive the Fe abundance of five objects only. A second problem is that the iron model atom in our TLUSTY models is too simplistic. Therefore, the line transfer in iron is treated in LTE (though the model atmospheres are NLTE). However, Thompson et al. (2007, *MNRAS* 383, 729) have shown that NLTE effects in Fe appear to be small. Typical errors in our results for iron are $\sim$0.2 dex.

Stanek: The table you show with abundances has many abundances below the average you adopt for both the LMC and SMC. Could you explain that?

de Koter: Indeed. In particular the table shows that the abundances of carbon and nitrogen are lower, reflecting that the LMC and SMC chemical composition is not simply a scaled Galactic case. However, C and N are not the most important elements driving the outflow (though C is significant for the hottest stars). The wind is driven by iron group elements, with significant contributions from silicon and sulphur. This is why we focus on these elements is settling on metallicity.

Konigsberger: How does the presence of magnetic fields effect the mass-loss rates?

de Koter: I see Stan jumping up and down and raising his finger. I think he would like to address this question.

Owocki: Well, the simplest answer is, "not much". But the fraction of the surface that is covered by closed loops can trap the wind and force it to fall back on the star, effectively reducing the global mass loss rate. The reduction can be ca. 50% for a strong field without rotation. With rotation, loops extending above the Kepler co-rotation radius eventually have centrifugal ejection of trapped wind, and so the net reduction in global mass loss is less. Further details can be found in a recent paper with Asif ud-Doula (*MNRAS*, in press; arXiv:0712.2780). There can also be a modest reduction (ca. 10%) of mass flux in open field regions due to the field tilt away from the surface normal. (see Owocki & ud-Doula, *ApJ* 600, 1004).

Stanek: Do you have any "mutants" in your analysis? (i.e. stars that don't fit)

de Koter: Our method did not signal clear cases of mutants, i.e. cases in which the derived parameters clearly signaled a non-physical solution. In part this is the result of preselection.

Massey: This is a followup to your statement that of these 86 O stars you got good fits for all of them. When we were analyzing our samples of LMC and SMC stars (Massey *et al.* 2004, *ApJ* 608, 1001; 2005, *ApJ* 627, 477) we failed to get satisfactory fits (by eye) to about a third of the stars. Presumably these were the composites (binaries) – not to sound like Dany. Are you concerned that your automatic fitting routines were always satisfied with their fits? Where are the spectral composites, then?

de Koter: To expand on my previous answer. There are two reasons why the automatic analyses we performed do not result in unsatisfactory fits in such a high fraction of the targets: 1) From the outset we excluded all known confirmed binaries and radial velocity variables. Therefore, one could say that in this respect our sample is preselected; 2) The automated method is much better in scanning all of parameters space as is a 'by eye' inspection of fits. Still, to be clear about this: in one case (star N11-048 in the LMC) the fit is very poor. We suspect the system to be a binary. In some cases the error bars are quite large (e.g. NGC 330-052) because of low signal-to-noise data, and in several cases one of the (set of potentially ten) diagnostic lines was fitted poorly.

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