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# An Interpretation of the Blue Satellite to Resonance Lines of Helium-like Ions of Third Sequence Elements in Laser-produced Plasmas

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*Abstract*

It is suggested that the blue satellite to resonance lines of helium-like ions of third sequence elements, observed in laser-produced plasmas by Boiko *et al.* (1974, 1975) and others and tentatively identified as a Baranger–Mozer satellite, is in fact the blue peak of the self-reversed resonance line profile which has been rendered asymmetrical (red peak enhanced and blue peak suppressed) by differential plasma motion. The various properties reported for the blue satellite are shown to be consistent with model calculations and with the known properties of optically thick, velocity-affected, resonance line profiles of second sequence elements in laser-produced plasmas. The tendency of the satellite to appear preferentially with conical accumulation is explained in terms of the smaller transverse velocities associated with accumulation. One implication of the present interpretation is that, with plane targets, the appearance of an asymmetrically self-reversed line as only a red peak may be the norm rather than the exception; with the further implication that plasma diagnostics based on the misidentification of the red peak as the line proper may be seriously in error.

## 1. Introduction

Satellites to the red or high wavelength side of resonance lines in laser-produced plasmas are frequently observed and have been extensively studied (see Boiko *et al.* 1978, and the references therein). Of present interest is the so-called blue satellite to resonance lines of helium-like ions of third sequence elements, whose occurrence in laser-produced plasmas has been reported by Boiko *et al.* (1974, 1975), Bayanov *et al.* (1976) and Aglitskii *et al.* (1977). The current status of experiment and theory regarding this satellite is reviewed in Section 2. This satellite has been tentatively identified by the above authors as a Baranger–Mozer satellite, though this identification is seen as controversial and needing further discussion. In Section 3 an alternative interpretation of the blue satellite is presented. Specifically, it is suggested that the 'blue satellite to the resonance line' represents the blue and red peaks respectively of the self-reversed resonance line profile which has been rendered asymmetrical by differential plasma motion. The various properties reported for the blue satellite are shown to be consistent with the known properties of asymmetrically self-reversed resonance line profiles of Stark broadened lines which are acknowledged as being velocity affected. In Section 4 model calculations are presented which further substantiate the interpretation in Section 3.

The blue satellite, or peak, appears preferentially in plasmas produced from a conical recess. This is explained (in Sections 3 and 4) in terms of the fact that such plasmas are characterized by smaller transverse velocities than plasmas from a plane target. The implication here is that, in plasmas from a plane target, the spectral line asymmetry is so great that, in general, only the red peak is of sufficient intensity to be observed; or, in other words, that the spectral feature normally labelled as the resonance line is but the red peak of a strongly asymmetric line profile. This implication is obviously far-reaching since it applies to optically thick lines of all ions (and not only helium-like ions) in laser-produced plasmas for which Stark broadening is negligible. The possible misidentification of the red peak as the line proper may have serious consequences, particularly with regard to plasma diagnostics, as discussed in Section 5.

To put this work into a broader context, we note that, in 1968, Fraenkel *et al.* reported what they described as high energy satellites to the resonance lines of Be III and IV in a vacuum spark plasma. Valero *et al.* (1969) and Ya'akobi and Goldsmith (1970) proposed that the 'high energy satellite to the resonance line' represented the blue and red peaks respectively of the asymmetrically self-reversed resonance line profile. According to Ya'akobi and Goldsmith the asymmetry was the result of a spatially varying plasma-polarization shift arising from a spatially varying temperature. As such, the observation can be catalogued with other observations of asymmetric self-reversals arising from spatially varying temperature and density, where the shift is due to pressure broadening (Cowan and Dieke 1948), resonance interaction (Braun *et al.* 1970) and electron impact broadening (Bober and Tankin 1969; Ya'akobi 1969*a*, 1969*b*). In the same category we have the asymmetric self-reversals observed in line radiation from crystals, where the asymmetry is due to strain-induced inhomogeneities (MacFarlane *et al.* 1976). A broad theoretical treatment of asymmetric self-reversals arising from spatial inhomogeneities, without necessarily specifying the shift mechanism, has been given by Gorbacheva and Preobrazhenskii (1963), Preobrazhenskii *et al.* (1965), Ilyin *et al.* (1969) and Braun *et al.* (1970). In the above cases the shift occurs principally in the emitting central region of the source. In the case of a laser-produced plasma of concern here, the asymmetry arises from differential plasma motion, where the shift is due to the Doppler effect and occurs principally in the absorbing outer region of the source. Spectral radiation from a hollow cathode lamp can also exhibit an asymmetry due to differential atom motion (De Jong and Piepmeier 1974; Piepmeier and De Galan 1975). Early in the discharge of the hollow cathode lamp the emitting atoms may be moving faster than the absorbing atoms (with the red peak suppressed and the blue peak enhanced) whereas late in the discharge the absorbing atoms may be moving faster than the emitting atoms (red peak enhanced and blue peak suppressed) (Piepmeier and De Galan 1975).

## 2. Current Status of Experiment and Theory

In a (neodymium) laser-produced plasma experiment, Boiko *et al.* (1974, 1975) have reported blue satellites to the resonance lines ($1s^2\,{}^1S_0$–$1s\,2p\,{}^1P_1$) of the helium-like ions Mg XI, Al XII, P XIV and S XV. These satellites were observed in the plasma produced when the laser pulse was focused into a conical depression but not when focused onto a flat surface. The spectra were apparently recorded without spatial resolution normal to the target surface. The satellites were observed along three different lines of sight, with no details given. Boiko *et al.* suggested that these were satellites of the Baranger–Mozer type, which were shifted relative to the frequency of the forbidden transition $1s^2\,{}^1S_0$–$1s\,2s\,{}^1S_0$ by the plasma frequency; a suggestion that has found support elsewhere (Ya'akobi 1976). For a discussion of satellites of this type, with reference to the above observations, the reader is referred to the reviews by Bekefi *et al.* (1976) and Peacock (1977).

Given the above interpretation, the frequency of the satellite line is dependent on the electron density $N_e$ (and therefore provides a valuable means of measuring $N_e$ in dense plasmas, as discussed by Vinogradov *et al.* (1974), which is one reason for the interest in these observations). However, since $N_e$ may be expected to vary in space and time during the period of emission of the helium-like radiation, we might ask why the satellite is seen as a well-defined line at all. Also, we must remark at the coincidence that, in each of the cases studied (including those mentioned below), the satellite should fall just on the blue side of the resonance line. In their paper, Boiko *et al.* (1974) refer to a resonance condition between the frequencies of the satellite line and of the resonance line. They comment that: 'The resonance condition "picks out" from the density profile in the cumulating plasma the values of $N_e$ listed in the table, which are apparently close to the maximal values'. The values of $N_e$ referred to in this quotation fall in the range $0\cdot64$–$1\cdot8\times10^{23}\ \mathrm{cm}^{-3}$, depending on the element concerned. Such values are significantly greater than the maximum value characteristic of the plasma produced from a plane target ($\sim10^{21}\ \mathrm{cm}^{-3}$). Boiko *et al.* associated these higher densities with an accumulation of plasma from the walls of the conical recess into the central region, henceforth referred to as conical accumulation (the term 'without accumulation' will sometimes be used to refer to the plasma from a plane target).

However, from the intensity ratio of the resonance and intercombination lines of Cl XVI, Boiko *et al.* (1974) deduced a value for $N_e$ of $\sim10^{21}\ \mathrm{cm}^{-3}$ with accumulation. This value is significantly smaller than the values of $\sim10^{23}\ \mathrm{cm}^{-3}$ deduced above, and 'is apparently averaged over space and time' (Boiko *et al.* 1974). The same measurement technique, applied in a second experiment to S XV (Boiko *et al.* 1975), led to a value of $N_e\sim1\cdot5\times10^{21}\ \mathrm{cm}^{-3}$ with accumulation, which was only about 70% greater than without accumulation. Bayanov *et al.* (1976) found that the value of $N_e$ deduced from Stark broadening (of Mg XII 1s–5p) with accumulation was comparable to that deduced without accumulation. In view of this and other measurements, Bayanov *et al.* concluded that the interpretation of the observed satellites as Baranger–Mozer satellites is 'controversial and needs further discussion'.

Bayanov *et al.* (1976) observed blue satellites to resonance lines of both the helium-like ion Mg XI and the *hydrogen-like* ion Mg XII, with (but not without) conical accumulation. The satellite decreased in intensity relative to the resonance line with increasing distance from the target, being undetected beyond distances of several hundred microns. Aglitskii *et al.* (1977) reported blue satellites to the helium-like ions S XV, Cl XVI and K XVIII *without* conical accumulation. The shift of the satellite with respect to the resonance line was reported to be of the same order as that observed by Boiko *et al.* (1974), though in some cases two satellites were observed, and the shift of the satellites varied with the laser flux.

The preceding observations, of the blue satellite without accumulation (where densities of $\sim10^{23}\ \mathrm{cm}^{-3}$ cannot be explained) and as a satellite to a hydrogen-like ion, are opposed to the interpretation of the blue satellite as a plasma satellite of the Baranger–Mozer type.* We note in passing that plasma satellites of the Baranger–Mozer type have not (to the author's knowledge) been reported elsewhere in dense ($N_e \geqslant 10^{21}$ cm$^{-3}$) plasmas and that, according to Burgess (1971), these are not the most likely satellites to appear under such conditions anyway. In the next section an alternative interpretation of the blue satellites is offered.

## 3. An Alternative Explanation

In Section 2 we reviewed observations of what have been described as 'blue satellites to resonance lines' of helium-like ions of third sequence elements in laser-produced plasmas. It is now proposed that what has been observed are the blue and red peaks respectively of the self-reversed resonance line profile which has been rendered asymmetrical (red peak enhanced and blue peak suppressed) by the differential plasma motion. In other words, it is proposed that the observations described in Section 2 fall into the same category as those for the resonance lines of Stark broadened hydrogen-like ions of second sequence elements, also in laser-produced plasmas, reviewed by Irons (1975) and reported more recently by Tondello *et al.* (1977), Jannitti *et al.* (1977, 1979), Nicolosi *et al.* (1978) and Malvezzi *et al.* (1979). In the same category we have the asymmetric self-reversals reported for the resonance lines of Be III and of Al IV, V and VI by Valero *et al.* (1969, 1970), and of Al V by Jaeglé *et al.* (1978). Of related interest are the astrophysical examples of velocity-affected line profiles described by Hummer and Rybicki (1968), Vaughan (1968), Linsky and Avrett (1970), Chiu *et al.* (1977), Snell and Loren (1977) and Brueckner *et al.* (1977).

The mechanism for the asymmetric self-reversal has been described in the astrophysical literature by, for example, Hummer and Rybicki (1968), Kunasz and Hummer (1974) and Vardavas (1976), and in the literature relating to laser-produced plasmas by Irons (1975) and Tondello *et al.* (1977). Briefly, consider a line of sight which, typically, is transverse to the axis of the expanding laser-produced plasma. Along this line of sight the component of expansion velocity towards the observer varies continuously from some value $+V$ at the near surface through zero on axis to $-V$ at the far surface. Plasma located between some point $\boldsymbol{r}$ in the source and the observer has a higher component of velocity towards the observer than does plasma at $\boldsymbol{r}$, and consequently absorbs preferentially on the blue side of the line profile radiated by ions at $\boldsymbol{r}$.

Extensive observations of velocity-affected resonance line profiles of hydrogen-like ions have been presented by Tondello and coauthors (see Tondello *et al.* 1977, and other references noted above) for laser-produced plasmas from plane targets. Inspection of these results, for the Stark broadened $L_\alpha$ transitions of Be IV – O VIII, prompts the following observations and comments.

(i) The intensity $I_B$ of the blue peak relative to the intensity $I_R$ of the red peak, and the spacing between the blue and red peaks, decrease with increasing distance from the target until, beyond a certain distance, the line profile becomes symmetrical. This trend, which is the same as that reported by Bayanov *et al.* (1976) for the 'blue satellites to resonance lines' of Mg XI and XII, can be understood (see the model

* Of related interest is the fact that the high energy satellites observed by Fraenkel *et al.* (1968) in a vacuum spark plasma (see Section 1) were considered not to be Baranger–Mozer satellites on the grounds that they occurred with the hydrogen-like ion Be IV (Ya'akobi and Goldsmith 1970).

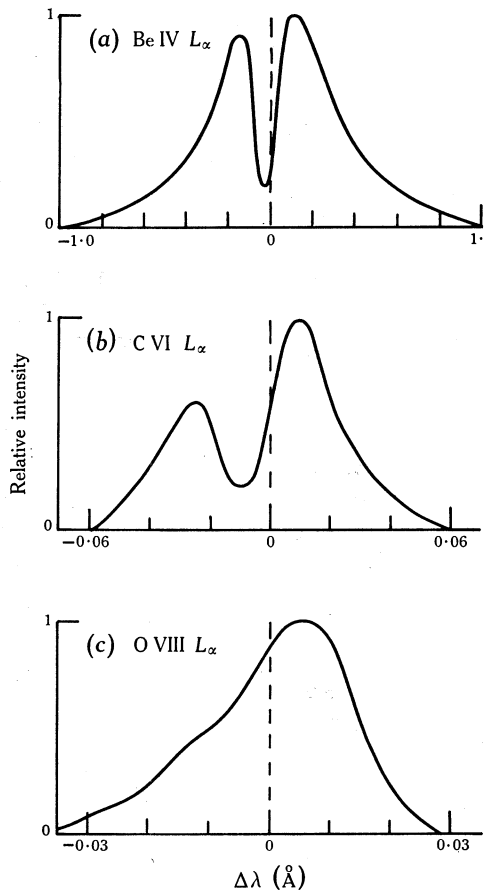


**Fig. 1.** Self-reversed Stark profiles for $L_\alpha$ transitions in (*a*) Be IV, (*b*) C VI and (*c*) O VIII, recorded at distances of 50, 60 and 60 $\mu$m respectively from the target surface (from Tondello *et al.* 1977; Nicolosi *et al.* 1978; Malvezzi *et al.* 1979). The profiles are rendered asymmetric by differential expansion. The ratio $I_B/I_R$ decreases as $Z$ increases, i.e. as the Stark half-width decreases and motional Doppler broadening becomes increasingly influential. (Note that 1 Å $\equiv 10^{-10}$ m.)

calculations of Irons 1975 or Jannitti *et al.* 1977) in terms of the decreasing opacity and increasing dominance of motional Doppler broadening with distance from the target.

(ii) The ratio $I_B/I_R$ near the target surface decreases with increasing atomic number $Z$ (see Fig. 1). This trend can be understood in terms of the fact that, with increasing $Z$, the intrinsic Stark broadening (which dominates thermal Doppler broadening for the lines concerned) decreases and the motional Doppler broadening accordingly becomes increasingly influential. An extrapolation of this trend to the limit where Stark broadening is negligible compared with thermal Doppler broadening (as with the resonance lines of helium-like ions)* would lead us to

* In principle one could observe this limit by looking at the $L_\alpha$ transition of higher hydrogen-like ions. However, for $Z \gtrsim 10$, fine-structure splitting becomes a complicating factor (Irons 1980).

conclude that, while the asymmetry is still present (at least near the target surface) the blue peak may be too weak to be observed.

It follows from (ii) above, that if close to the target (we are only interested in the region of plasma within a few hundred microns of the target surface, where the blue satellites are observed) the expansion of the plasma were jet-like with a small transverse velocity (as from a conical depression), rather than plume-like with a comparatively large transverse velocity (as from a plane target), then we could expect the motional Doppler broadening along the line of sight to be less dominant and the blue peak to be correspondingly stronger and more detectable. This then would explain the fact that the blue satellite is observed principally when the laser is focused into a conical depression. To preserve the main flow of the argument, a discussion of the experimental evidence regarding the variation in transverse velocity with and without conical accumulation is postponed until the end of this section.

We have just drawn a *relative* distinction between the plasma from a conical depression and from a plane surface, i.e. we have suggested that the plasma from a conical depression is *more* collimated, with a *smaller* transverse velocity, than from a plane surface. This is not to imply that the plasma from a plane surface cannot sometimes be collimated, in fact highly collimated (see Feldman *et al.* 1976; Doschek *et al.* 1977), and that the transverse velocities in plasmas from plane surfaces cannot sometimes be sufficiently small for the blue satellite to helium-like ions of third sequence elements to appear (Aglitskii *et al.* 1977).

The velocity gradient needed to render the line profile asymmetrical is present along a multitude of lines of sight, and not just a line of sight which is normal to the axis of expansion. It is not surprising therefore that Boiko *et al.* (1974), when observing the plasma along three different directions, should find that 'the form of the spectrum does not depend on the registration direction'. It is also to be expected that the expansion characteristics will be a function of the laser flux. It is also not surprising therefore that Aglitskii *et al.* (1977) should observe that the spacing of the red and blue peaks varies with the laser flux.

Hence, all the properties ascribed to the blue satellites can be qualitatively explained in terms of differential plasma motion. We recall that Aglitskii *et al.* (1977) reported not one, but two blue satellites (to the resonance line of Cl XVI in the plasma from a plane KCl target). The precise explanation of this observation in terms of differential motion is not clear but we note that, in another experiment with a plane KCl target and comparable laser parameters (Feldman *et al.* 1976), spectroheliograms showed the presence of multiple structure within the expanding plasma.

One further point of comparison is noteworthy. Consider that the laser-produced plasma is observed at a specific distance from the target, with spatial resolution parallel to the target surface. It is evident from the observations of Be IV $L_\alpha$ by Jannitti *et al.* (1979) (and to a lesser extent from the observations of resonance lines of Be III and IV and Al IV, V and VI by Valero *et al.* 1969, 1970) that the spacing between the red and blue peaks is greatest for a diametrical line of sight (i.e. passing through the expansion axis) and decreases for chordal lines of sight with distance from the expansion axis, as also does the ratio $I_B/I_R$; until in the plasma periphery a single line is observed, the wavelength of which (approximately equal to the normal line centre) lies just on the blue side of the red peak observed diametrically.

Interestingly enough these trends can be discerned in the spectrum photograph presented by Boiko *et al.* (1975), which shows the 'blue satellite' and 'resonance line' of P XIV spatially resolved parallel to the target surface (compare this spectrum photograph with that in Fig. 3 of Jannitti *et al.* 1979; and in Fig. 7 of Valero *et al.* 1970).

Finally, we turn to the experimental evidence regarding the variation in transverse velocity with and without conical accumulation. While there have been a number of experiments devoted to the study of plasmas produced when laser radiation is focused into a conical depression (in addition to those mentioned in Section 2 above; see Gribkov *et al.* 1975, 1978; Bykovskii *et al.* 1978; and the references therein), there is very little quantitative information on the transverse component of expansion velocity. Kononov (1978) comments (but gives no source reference) that when a laser is focused into a hollow in a target 'the expansion component along the target surface is small and narrow lines can be obtained'. Bykovskii *et al.* (1978) have measured (at 15 cm from the target) the angular distribution of maximum and average ion velocities when the laser is focused into a conical depression. For the cone angles (of $2\alpha \leqslant 90°$) considered by Bykovskii *et al.*, the transverse velocity was approximately three times smaller than from a plane target ($2\alpha = 180°$). Bayanov *et al.* (1976) observed the (presumably optically thin) intercombination line Mg XI $1s^2\,{}^1S_0$–$1s\,2p\,{}^3P_1$, and found that beyond $\sim 500\,\mu m$ from the target the Doppler half-width was about three times smaller with conical accumulation than without accumulation,* in broad agreement with the results of Bykovskii *et al.* However, within $\sim 300\,\mu m$ of the target the half-width of the intercombination line was found to be approximately the same with and without accumulation. The same result was reported for the resonance line Mg XI $1s^2\,{}^1S_0$–$1s\,2p\,{}^1P_1$, a fact which is of interest later in Section 5*b* below.

The above observations are the only ones of their kind known to the author. There is a need for further experiments which compare the transverse velocity component with and without conical accumulation, for individual ion species within a few hundred microns of the target, preferably in conjunction with observations of the blue satellite.

## 4. Model Calculations: Comparison with Experiment

The effect of differential plasma motion on emergent line profiles, as described qualitatively in the previous section, is illustrated in the literature by model calculations performed for laser-produced plasmas. The calculations of Jaeglé and coworkers illustrate how the emergent line profile varies with absorbing ion density and collisional broadening (Jaeglé *et al.* 1978) and with the apparatus function and the spatial profile of absorbing ion density (Jamelot *et al.* 1978). Tondello and coworkers (Tondello *et al.* 1977, and other references noted in Section 3) have matched model calculations to observed profiles, as a function of distance from the target. Irons (1975, 1976) has mapped emergent profiles and intensities for a wide range of plasma parameters.

* The caption to Fig. 7 of Bayanov *et al.* (1976) appears to contain a misprint since it disagrees with the description of the results contained in Sections III 3 and IV of the main text. Presumably the results attributed (in the caption) to a plane target should be attributed to the target with a recess, and vice versa.

As far as the observations described in Section 2 are concerned, there are insufficient data available for a quantitative theoretical comparison. However, we can at least compare the observations with the model calculations of Irons (1975). Consider the following set of parameters, which are typical of the resonance line of Mg XI in the immediate vicinity of the target surface:

(1) a ground state density $n_1(\mathrm{Mg}^{10+}) \approx N_e/3(Z-2) \approx 3\times 10^{19}\ \mathrm{cm}^{-3}$, when $N_e = 10^{21}\ \mathrm{cm}^{-3}$ and $Z = 12$;

(2) a plasma dimension $D = 0{\cdot}01$ cm (Boiko *et al.* 1975);

(3) an ion temperature (equal to the electron temperature) of $kT = 500$ eV (Boiko *et al.* 1974), implying a (unidirectional) mean thermal velocity of $\langle v\rangle \approx 3\times 10^6\ \mathrm{cm\,s^{-1}}$ and an HWHM of

$$\lambda_{\frac{1}{2}} = \lambda_0\left(\frac{kT\,2\ln 2}{M}\right)^{\frac{1}{2}} = 0{\cdot}0016\ \text{Å} \qquad \text{or} \qquad \nu_{\frac{1}{2}} = 5{\cdot}8\times 10^{13}\ \mathrm{s}^{-1};$$

(4) a line-of-sight component of expansion velocity at the plasma surface of $V = 1\times 10^7\ \mathrm{cm\,s^{-1}}$ (transverse velocities of this order are characteristic of laser-produced plasmas; see e.g. Irons *et al.* 1972), corresponding to a wavelength shift of $\lambda(\frac{1}{2}D) = \lambda_0\, V/c = 0{\cdot}0030$ Å.

The optical depth at line centre for the plasma when at rest (i.e. ignoring differential motion) is, for thermal Doppler broadening,

$$\tau_0 = (\pi e^2/mc) f\, n_1(\mathrm{Mg}^{10+})\, D(\pi^{-1}\ln 2)^{\frac{1}{2}}\,\nu_{\frac{1}{2}}^{-1} \approx 40\,,$$

given the values in the parameter set (1)–(4).

Now define a parameter

$$\eta = \lambda(\tfrac{1}{2}D)/\lambda_{\frac{1}{2}}\,, \tag{1}$$

where, in the present case, $\lambda_{\frac{1}{2}}$ refers to the thermal Doppler HWHM (if Stark broadening were significant then $\lambda_{\frac{1}{2}}$ would have to be adjusted accordingly). Since $\lambda_{\frac{1}{2}}$ refers only to the thermal Doppler HWHM, we have $\eta \approx V/\langle v\rangle$. ($\eta$ is precisely equal to $V/v_{\frac{1}{2}}$, where $v_{\frac{1}{2}}$ denotes the HWHM of the unidirectional thermal Doppler distribution; however, $v_{\frac{1}{2}}$ is not a commonly used parameter.) Our general expectation for laser-produced plasmas is that, close to the target surface, $V$ is of the same order as $\langle v\rangle$ and perhaps several times greater, implying values of $\eta$ in the approximate range 1–3. The above calculations for Mg XI give (from equation 1) $\eta \approx 2$, and thus exemplify this expectation. Hence, although the following analysis refers specifically to Mg XI, it is pertinent in general to optically thick lines in laser-produced plasmas with negligible Stark broadening.

Irons (1975) has mapped the emergent line profile as a function of $\tau_0$ and $\sigma$,* for a gaussian (and a lorentzian) emission profile, for a velocity gradient which is constant in geometric space and for two models (models AI and B) which describe the spatial distribution of ions in the upper and lower states. Model AI, for a constant source function, does not lead to a self-reversal and is not pertinent to the

* The parameter $\sigma$ used in the previous publication has been replaced here by the physically more useful $\eta$ ($\equiv\sigma^{-1}$).

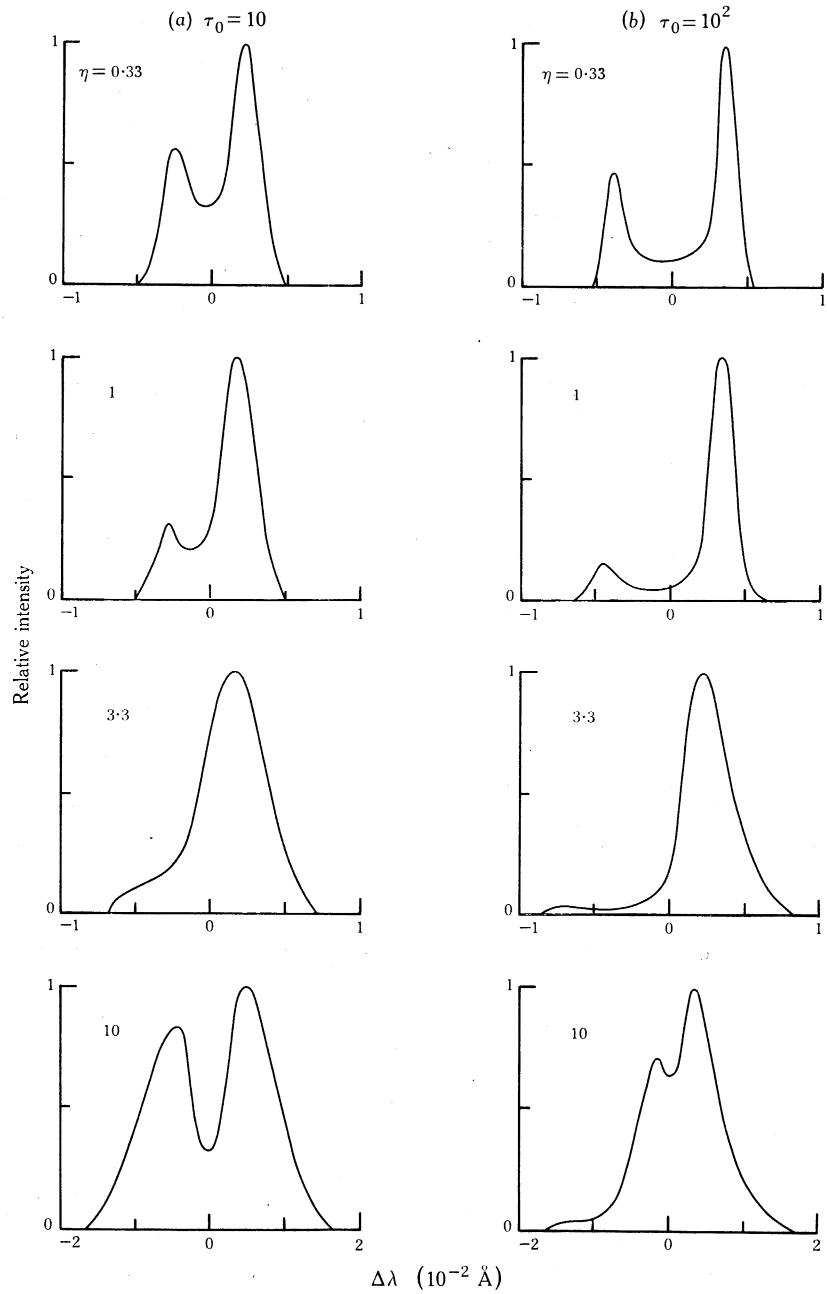


**Fig. 2.** Computed emergent line profiles for a gaussian emission profile, with (*a*) $\tau_0 = 10$ and (*b*) $\tau_0 = 10^2$, and for the indicated values of the parameter $\eta$, which is defined by equation (1). Each profile is normalized to unit peak intensity.

present study. Fig. 2 here shows profiles taken from Fig. 5 of Irons (1975), which is for a gaussian emission profile and for model B; the abscissa $\Delta\lambda/\lambda_{\frac{1}{2}}$ in Fig. 5 of Irons (1975) having been multiplied by $\lambda_{\frac{1}{2}} = 0\cdot0016$ Å to give the abscissa $\Delta\lambda$ in the present Fig. 2. The profiles selected for reproduction in Fig. 2 correspond to parameters $\tau_0 = 10$ and $10^2$ and $\eta = 0\cdot33$, 1, $3\cdot3$ and 10, which encompass the values of $\tau_0 \approx 40$ and $\eta \approx 2$ calculated above.

We see from Fig. 2 that even when $\eta = 0\cdot33$ (i.e. even when motional Doppler broadening amounts to only one-third of the thermal Doppler broadening) the line profile is markedly asymmetrical, with the red peak enhanced and the blue peak suppressed compared with their magnitudes in the absence of differential motion. As $\eta$ increases, i.e. as motional Doppler broadening becomes increasingly important, so the asymmetry increases. Of particular interest is the fact that a variation by a factor of 3 in $V$ can mean the difference between observing a blue peak ($\eta = 1$) and not observing a blue peak ($\eta = 3\cdot3$), and that a variation of this order represents the difference between focusing the laser into a conical depression and onto a plane surface (see Section 3). As $\eta$ increases further, to 10, i.e. as motional Doppler broadening exceeds the thermal Doppler broadening by an order of magnitude, it is no longer helpful to think of the emergent profile in terms of a basically self-reversed profile modified by differential motion, but rather we may refer to the discussion in Irons (1975). In present-day laser-produced plasmas, values of $\eta \approx 10$ are only likely to be achieved far from the target where $\lambda_{\frac{1}{2}}$ is small. However, far from the target $\tau_0 \approx 0$, so the profiles in Fig. 2 for $\eta = 10$ represent a regime which is probably not observable.

For $\eta = 1$ the spacing between the blue and red peaks in Fig. 2 is $\sim 0\cdot006$ Å, which compares favourably (more favourably than one is entitled to expect for these model calculations) with the observed spacing of $0\cdot008$ Å for Mg XI $L_\alpha$ (Boiko *et al.* 1974). A similar comparison for the other ions (Al XII – S XV) observed by Boiko *et al.* (1974) is only marginally less favourable.

We conclude therefore that the preferential appearance of the blue satellites with conical accumulation, and the wavelength separation of the red and blue peaks, are in qualitative agreement with theory, as represented by the above model calculations.

## 5. Implications of the Present Interpretation

It is apparent from the foregoing that the appearance or otherwise of the blue peak is sensitively dependent on the magnitude of motional Doppler broadening relative to intrinsic broadening. When the motional Doppler broadening is reduced (by conical accumulation) or when the intrinsic broadening is increased (by a strong Stark contribution) the blue peak is observed. When the plasma is formed from a plane target and when there is no obviously strong Stark broadening, the blue peak may be observed (as with the resonance lines of Al IV, V and VI and of the helium-like ions Be III, S XV, Cl XVI and K XVIII mentioned in Sections 2 and 3), but the paucity of observations of self-reversed lines in laser-produced plasmas (due in some measure to the need for good spatial resolution, as discussed by Irons 1975) indicates that in general the blue peak is not present. The implication is that the appearance of an optically thick line close to the target as only a red peak is the norm rather than the exception.

If the blue peak is not present then, clearly, the red peak is likely to be mistaken for the line proper. Indeed, even when the blue peak *is* observed it may be mistaken for a satellite, and the red peak may still be mistaken for the line proper (as in Section 2). Comments to this effect are contained in an earlier paper (Irons 1975). The consequences of such a misidentification will now be examined.

### (*a*) *Wavelength Determination*

In principle, errors may occur in the wavelength determination of newly observed lines if:

(1) the newly observed line is optically thick and the feature being observed is the red peak, or

(2) the red peak of an optically thick line is used as a wavelength standard but is assigned the wavelength of the normal line centre.

In the case of the resonance line of Mg XI, the error concerned is $\sim 0 \cdot 002$ Å (see Fig. 2), which is marginally greater than the quoted error in the measured wavelengths of resonance lines of helium-like and hydrogen-like ions of early third sequence elements in laser-produced plasmas (Aglitskii *et al.* 1974). In practice the error may be much smaller than just indicated since many spectra are recorded without spatial resolution and the asymmetry is present only within a few hundred microns of the target surface. Aglitskii *et al.* (1974) have compared the wavelengths measured (apparently without spatial resolution) for the resonance lines mentioned above with theory and with measurements from other sources (the vacuum spark and the solar corona). Inspection of their results shows no evidence for the type of error indicated above.

Bayanov *et al.* (1976) have presented line profile observations of Mg XI $1s^2\,{}^1S_0$–$1s\,2p\,{}^1P_1$, in their Fig. 6, which shows the red peak of the asymmetrical profile close to the target as having the same wavelength as the symmetrical, (probably) optically thin profile far from the target, the latter wavelength being (in all probability) equal to the normal line centre. However, this may be an *a priori* assignment, rather than the result of an actual measurement. An unambiguous determination of the normal line centre is needed to settle this point.

### (*b*) *Plasma Diagnostics*

Any analysis of the red peak assuming it to be the line proper is obviously fraught with error. The half-width cannot be interpreted on the basis that the optically thin line is being observed. Taking as an example the profiles in Fig. 2 for $\eta = 1$ and $3 \cdot 3$, we note firstly that the red peaks of these profiles are deceptively symmetrical, and secondly that the HWHM values of the red peaks fall in a range ($1$–$2 \times 10^{-3}$ Å) which is deceptively consistent with the thermal Doppler HWHM of $1 \cdot 6 \times 10^{-3}$ Å. Our normal expectation for opacity does us a disservice here. Opacity would normally be seen as an effect which increases the apparent half-width; so, while an observed half-width greater than what could be explained in terms of thermal plus motional Doppler broadening might be viewed with suspicion, an observed half-width smaller than this value would be acceptable; and would be interpreted, for example, as indicating that motional Doppler broadening was smaller than imagined. The experiment of Bayanov *et al.* (1976) is interesting in this regard. They report that the broadening of the 'resonance line' of Mg XI close to the target is the same as that of the (presumably optically thin) intercombination line, and they deduce (equal) velocities from both profiles. We note also the difficulty expressed by Key *et al.* (1978) in obtaining a self-consistent analysis of the resonance lines of hydrogen-like and helium-like ions in plasmas produced from pellet targets. It is interesting to speculate whether the rather more complex pattern of differential motion associated with an ablating–imploding pellet is responsible for the observation of Al XIII $L_\alpha$ as a central peak with both red and blue satellites (Key *et al.* 1978).

The interpretation of the intensity of an optically thick line to give an accurate value of the population density of the emitting state is a difficult problem even for a stationary plasma. In a moving plasma the velocity field is an additional parameter to be considered. The question of misidentification is not so critical when the line intensity is at issue, unless the blue peak is of comparable intensity to the red peak (as in the case of Bayanov *et al.* 1976). The determination of density and temperature from intensity ratios involving the resonance lines of helium-like and hydrogen-like ions is subject to the effect of opacity, though this effect is usually neglected. The presence of differential motion, which reduces the plasma opacity, does not in itself justify this neglect, though it does make it more plausible.

## 6. Conclusions

The so-called 'blue satellites' to 'resonance lines' of helium-like ions of third sequence elements observed in laser-produced plasmas have been identified here as the blue and red peaks respectively of the self-reversed resonance line profile rendered asymmetric by differential plasma motion. The various properties reported for the blue satellites are consistent with model calculations and with the known properties of asymmetrically self-reversed resonance line profiles of second sequence elements in laser-produced plasmas. The tendency of the blue satellite, or peak, to appear preferentially with conical accumulation has been explained in terms of the smaller transverse velocities which, as shown by a limited number of experiments, accompany conical accumulation. It has been suggested that the appearance of an optically thick line as only a red peak may be the norm rather than the exception close to the target in plasmas produced from plane targets. The misidentification of the red peak as the line proper may have serious consequences, particularly with regard to plasma diagnostics, as discussed in Section 5. The need for further experimentation has been emphasized at various points throughout this study.

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