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Stark Broadening of Co II Lines in Stellar Atmospheres

Zlatko Majlinger [1], Milan S. Dimitrijević [1,2,*] and Vladimir A. Srećković [3]

1 Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia; zlatko.majlinger@gmail.com
2 Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, F-92195 Meudon, France
3 Institute of Physics Belgrade, University of Belgrade, 11001 Belgrade, Serbia; vlada@ipb.ac.rs
* Correspondence: mdimitrijevic@aob.bg.ac.rs; Tel.: +381-64-297-8021

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Abstract: Data for Stark full widths at half maximum for 46 Co II multiplets were calculated using a modified semiempirical method. In order to show the applicability and usefulness of this set of data for research into white dwarf and A type star atmospheres, the obtained results were used to investigate the significance of the Stark broadening mechanism for Co II lines in the atmospheres of these objects. We examined the influence of surface gravity (log g), effective temperature and the wavelength of the spectral line on the importance of the inclusion of Stark broadening contribution in the profiles of the considered Co II spectral lines, for plasma conditions in atmospheric layers corresponding to different optical depths.

Dataset: Supplementary File

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Keywords: atomic data; stark broadening data; line profiles; Co II; white dwarfs; A-type stars

1. Introduction

The importance of Co II spectral lines, weak or strong (weak lines of Co II could help in the better adjustment of cobalt abundance measured on the basis of existing strong Co I lines), for the cobalt abundance determination in the spectra of A to F type stars, has been discussed elsewhere [1]. For this reason, Stark full widths at half maximum for 46 Co II multiplets have been calculated [2,3] to be helpful for astrophysical purposes. Calculation for all 46 multiplets were done using the modified semiempirical method (MSE) [4]. Stark broadening of spectral lines is the dominant broadening mechanism in the cases of high-temperature and dense plasma which can be found in hot star atmospheres. It is noticed that disregarding the Stark broadening effect in the process of spectral line synthesis can produce a worse fit of synthetic with observed spectral lines (see, for example, [5]), or can cause errors in abundance determination, especially for A-type stars ([6], for example).

In this paper, the applicability and usefulness of an electron-impact broadening dataset for Co II lines for investigations of white dwarf and A-type star atmospheres is analyzed. Stark broadening of the lines in the spectra of hot and dense celestial objects such as white dwarfs (WD), because of specific conditions of high electron density and high temperature in their atmospheres, usually dominates on Doppler broadening. Consequently, particular attention has been payed to hydrogen-rich (DA) and helium-rich (DB) types of WD, trying to figure out if a change in the physical conditions in their atmospheres, such as effective temperature or surface gravity, affects the relationship between thermal Doppler and electron-impact broadening for particular spectral lines.

2. Dataset and Methods of Research

Stark broadening theory has its application both in laboratory research as well as in astrophysical plasma [4,7–12]. For example, from the astrophysical point of view, Stark broadening data are always of interest when the Stark broadening contribution to the considered line profile is not negligible, such as in the cases of the interpretation, synthesis and analysis of stellar spectral lines, the determination of chemical abundances of elements from equivalent widths of absorption lines, the calculation of radiative transfer through stellar atmospheres and subphotospheric layers, opacity calculations, radiative acceleration considerations, nucleosynthesis research and other astrophysical topics. In the investigation of laboratory plasma, Stark broadening theory can help, for example, in plasma diagnostics, for the determination of the density and temperature of the plasma.

The importance of cobalt is equally present in technology as in astrophysical research. Cobalt is, for example, used in the preparation of magnetic and wear-resistant alloys. Lithium cobalt oxide as a cobalt compound is widely used in lithium ion battery cathodes. Cobalt-60 is a commercially important radioisotope, used as a radioactive tracer and as a source of high energy gamma rays.

From the perspective of astrophysical science, cobalt is important in the spectral analysis of so-called chemically peculiar (CP) stars. The main characteristic of these stars is anomalous strong or weak absorption lines in their spectra in comparison with the solar spectrum [13], so the investigations of those spectra are of particular interest for the modelling of CP star atmospheres as well as in the research of stellar evolution. The special part of these investigations is line shape modelling for comparison with actual measured spectra where lines of transition metal ions, such as singly ionized cobalt, are observed.

Thus, spectral lines of singly charged cobalt ion (Co II), for example, have been observed in Hg-Mn stars [14]. The persistence of large cobalt deficiency in the atmospheres of those objects, with metalicity of the order of −2 dex is noticed [15]. It is also very interesting to investigate another subgroup of CP stars, so-called cobalt stars (Co-stars), where an anomalous excess of cobalt abundance is observed in their spectra. Cobalt stars are mostly Ap-type, sometimes Bp-type, often having strong magnetic fields (5 kG or more). Examples of Co-stars are the Bp star HR 1094 [16], the Ap stars HD 200311 [17], HD 203932 [18] and possibly HD 208217 [19] and HR 4059.

Stellar iron, nickel and cobalt are also products of nuclear burning in a supernova event. Their strong absorption lines can be found in supernovae of types Ia and II [20] as a result of explosive nucleosynthesis. The stable form of cobalt is produced in supernovae through the so-called r-process, which occurs in their core-collapse and is responsible for the creation of approximately half of the neutron-rich atomic nuclei heavier than iron. The process entails a succession of rapid neutron captures (hence the name r-process) by heavy seed nuclei, typically ^{56}Fe or other more neutron-rich heavy isotopes.

The first spectrum analysis of Co II was by Meggers [21], who measured the spectrum between 2150 and 5000 Å, and found eight multiplets and identified 14 lines of Co II in the solar spectrum. The analysis was extended by Findlay [22], Hagar [23], Velasco and Adames [24] and by Iglesias [25,26]. Iglesias commented that among the second spectra of the iron group elements, one of the most incompletely known spectra was that of Co II. The critical compilations of energy levels of Co II from more recent times which are also used in our calculations are from Sugar and Corliss [27] and Pickering et al. [28]. Pickering recorded high-resolution spectra of singly ionized cobalt by Fourier transform spectrometry in the region 1420–33,333 Å with cobalt-neon and cobalt-argon hollow cathode lamp as a source [28,29] and, therefore, it further contributed to the completion of the knowledge of these complex spectra.

The observed levels in Co II belong to two configuration systems. The "normal" system consists of $3d^7(^M L)nl$ subconfigurations, which are built on the parent terms (^{M}L) in Co III, and transitions involving these levels dominate the emission spectrum of Co II. The subconfigurations $3d^6(^M L)4snl$ in the "doubly excited" system are built on the (^{M}L) grandparent terms in Co IV, and they were not part of our interests. The Stark widths analyzed and used here [2,3] were calculated for multiplets created from a normal system of configurations, $3d^7(^ML)nl$, which is well known for nl = 4 s and 4p, and according to observations those transitions are expected to be in pure LS coupling [28]. The predicted accuracy of the MSE method is around ±50 percent, but even in the cases of emitters with complex spectra, for example Xe II and Kr II, this method often gives better agreement with experiments, with relative error less than ±30 percent [30,31]. Of course, the used model also has some error bars, but our qualitative conclusions are confirmed with calculations using three different papers with model atmospheres for DA and DB white dwarfs and for A type stars. A high precision can not be achieved since we used the published models and included Stark broadening of spectral lines a posteriori. However, the presence of Stark broadening influence electron density and temperature and, consequently, on parameters of the model of atmosphere and for the best precision the Stark broadening data should be introduced a priori, during the calculation of model atmosphere.

For the purpose of this work, we chose four lines from the list of 46 Co II spectral lines for which Stark widths have already been calculated and published elsewhere [2,3], and we investigated if atmospheric layers with possible domination of Stark broadening over the thermal Doppler broadening for each of these four lines exist (Figures 1–6) To show this, different models of atmosphere of A-type star and DA and DB WD were used. Stark and Doppler broadening were presented as a function of optical depth or temperature of atmospheric layers. For investigation of this dependence, which is shown in Figure 3a,b, the Kurucz model of A spectral type of a star was used with the logarithm of surface gravity log g = 4.5 and effective temperature T_{eff} = 10,000 K [32]. In the case of DA and DB dwarfs, the results of similar investigations are presented in Figures 1 and 2, using the model atmospheres from Wickramasinghe [33]. For the presentation of this dependence according to different T_{eff} or log g for DB stars, appropriate model atmospheres from Koester were used [34].

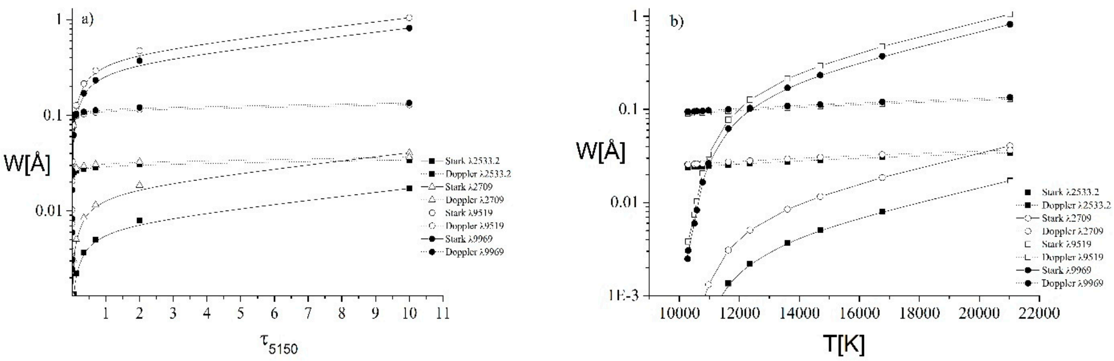

Figure 1. (**a**) Stark and Doppler broadening for spectral lines λ2533.2, λ2709, λ9519 and λ9969 as a function of optical depth in the atmosphere of a hydrogen-rich (DA) white dwarf. Model atmosphere with T_{eff} = 15,000 K and log g = 8 is taken from [33]. (**b**) Same as Fig1a, but as a function of atmospheric layer temperature instead of optical depth.

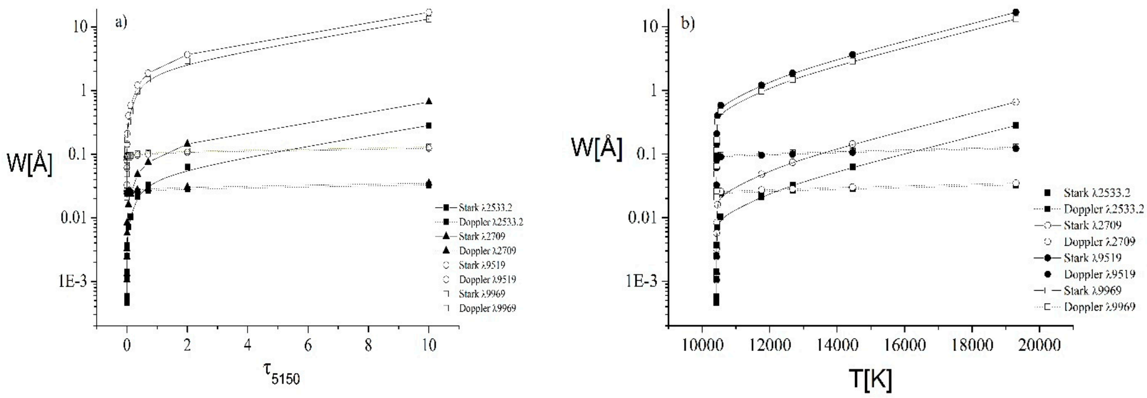

Figure 2. (**a**) Same as in Figure 1a, but for the model atmosphere of a helium-rich (DB) white dwarf [33], with same model parameters, T_{eff} = 15,000 K and log g = 8. (**b**) Same as Figure 2a, but as a function of atmospheric layer temperature instead of optical depth.

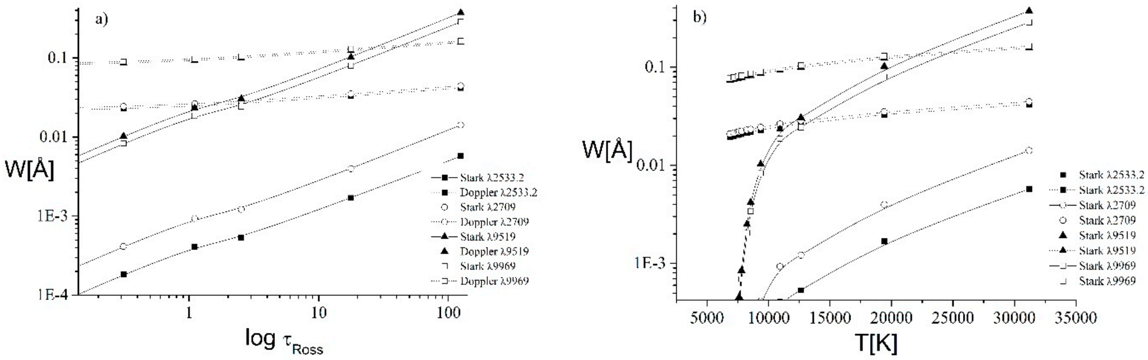

Figure 3. (**a**) Same as in Figures 1a and 2a, but as a function of logarithm of Rosseland optical depth, for the model atmosphere of A-type star [32] with model parameters log g = 4.5 and T_{eff} = 10,000 K. (**b**) Same as Figure 3a, but as a function of atmospheric layer temperature instead of optical depth.

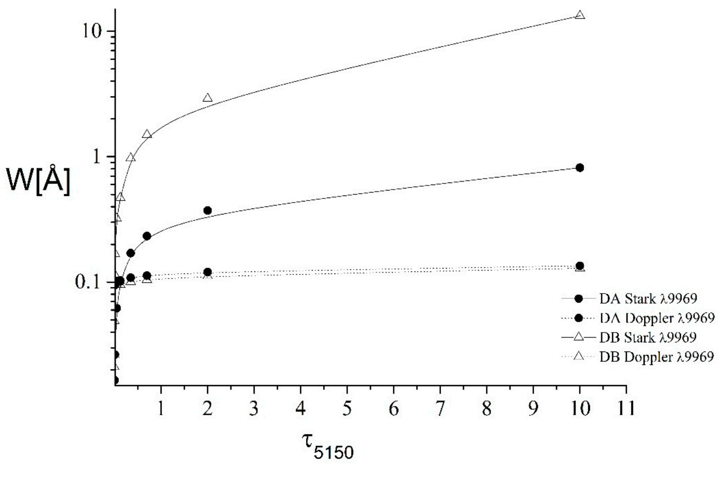

Figure 4. Comparison of Stark and Doppler broadening influence on Co II line λ9969 in the atmosphere of DA and DB white dwarfs, respectively, as a function of optical depth. Calculations have been performed for model atmospheres of DA and DB white dwarfs [33] with the same model parameters as in previous figures, T_{eff} = 15,000 K and log g = 8.

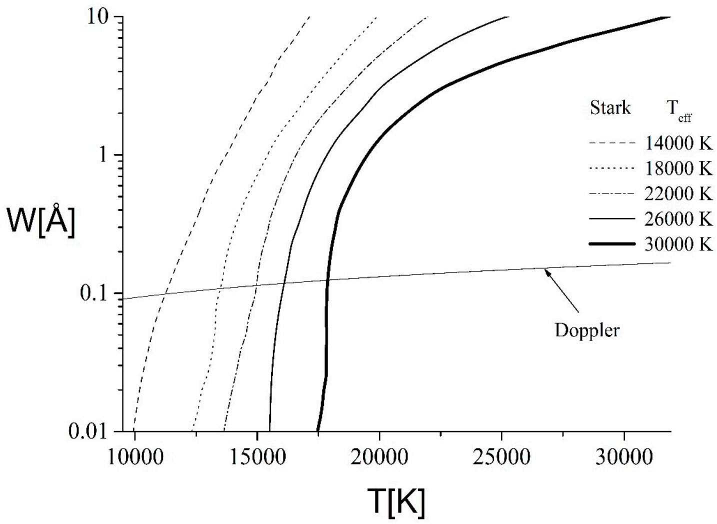

Figure 5. Stark and Doppler broadening of Co II spectral line λ9969 as a function of temperature of atmospheric layers in a DB white dwarf. Stark widths are shown for models [32] with five different values of effective temperature, T_{eff} = 14,000–30,000 K and log g = 8.

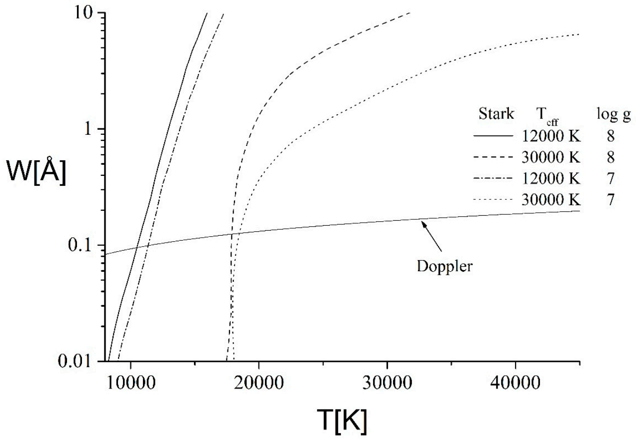

Figure 6. Stark and Doppler broadening of Co II spectral line λ9969 as a function of temperature of atmospheric layers in a DB white dwarf for two different values of model gravity, log g = 7 and log g = 8, each with two extremal values of effective temperatures, T_{eff} = 12,000 K and T_{eff} = 30,000 K.

3. Results and Discussion

In Figures 1–3, the comparisons of Stark widths and Doppler widths of λ2533.2, λ2709, λ9519 and λ9969 Co II spectral lines as a function of the optical depth in the white dwarf and A-star atmospheres are presented, to show in which layers of stellar atmosphere Doppler broadening caused by thermal motion of particles is dominated by Stark broadening caused by impacts of Co II ions with electrons.

In astrophysics, optical depth is a measure of the extinction coefficient or absorptivity, integrated from zero towards deeper layers up to a specific depth in stellar atmosphere. So, it is local characteristic as with electron temperature and it increases from zero towards deeper layers. Because it varies with wavelength, it is usually given for a standard wavelength of 5150 Å or as the Rosseland mean optical depth averaged over frequencies. Since we use published models of stellar atmospheres, we use optical depth as provided by authors of the models.

The first two lines, λ2533.2 and λ2709, from multiplets $(^4P)4s\ ^3P$–$(^4P)4p\ ^3D^o$ and $(^4F)4p\ ^3G^o$–$(^4F)5s\ ^3F$, respectively, are in the ultraviolet part of the spectrum, while the last two lines considered by us, λ9519 and λ9969, from multiplets $(^4F)5s\ ^5F$–$(^4F)5p\ ^5G^o$ and $(^4F)5s\ ^3F$–$(^4F)5p\ ^5F^o$, respectively, are in the infrared part of the spectrum. In Figure 1a,b, this analysis is done for DA WD model atmospheres [33] with parameters T_{eff} = 15,000 K and log g = 8. Stark and Doppler broadening as a function of optical depth τ in the atmosphere at 5150 Å are shown in Figure 1a, and as a function of layer temperature in Figure 1b. The same comparisons but for DB white dwarf atmosphere model with the same parameters are shown in Figure 2a,b. In Figure 3a,b, we can see the behaviors in the function of logarithm of Rosseland optical depth and temperature in the stellar atmospheres for an A-type model atmosphere [32] with parameters log g = 4.5 and T_{eff} = 10,000 K. Stark width in comparison with Doppler width increases as wavelength increases, because if a wavelength is larger than the corresponding atomic energy levels are closer and because of that, the perturbation of the emitter/absorber is larger and the emitted spectral line is broader. We notice also that Stark widths are proportional to λ^2, while Doppler widths are proportional to λ [3]. For the last line, λ9959, the point where Stark width reaches Doppler width is deeper in the atmosphere than for the previous line, λ9519, because the Stark width values for this line are smaller since the corresponding atomic energy levels are further away than in the previous case and the perturbation is smaller.

We can see that for the hydrogen-rich (DA) type of WD, Stark broadening starts to be more significant than the Doppler broadening already in the atmospheric layers with relatively smaller optical depth, for spectral lines λ9519 and λ9969 near to $\tau \approx 0.5$. Electron-impact broadening for the line λ2709 becomes more significant for layers after $\tau \approx 10$, while for line λ2533.2 Doppler broadening is dominant for all considered values of optical depth. For the helium-rich (DB) type of WD, domination of Stark broadening for all four lines over the Doppler broadening starts before optical depth $\tau \approx 1$, where most of spectral lines are formed, so we can expect that electron-impact broadening for all three lines should be more important than thermal broadening in DB dwarf spectra. Difference between the importance of Stark broadening in comparison with Doppler broadening between DA and DB type of WD is in favor of DB type, because a helium-rich (DB) dwarf can generate more free electrons than the hydrogen-rich (DA) dwarf with the same density, causing higher perturber density [3]. This advantage in the domination of Stark width over Doppler width in the DB type in comparison with the DA type is also obvious from Figure 4, where these widths are presented as a function of optical depth.

From the same analysis for an A-type stellar atmosphere, we can see that for the spectral lines λ9519 and λ9969, Stark broadening also becomes the most significant broadening mechanism, but after reaching the deeper layers of the atmosphere, around optical depth of $\tau \approx 50$ and $\tau \approx 70$ respectively, e.g., for temperatures of atmospheric layers around 20,000 and 25,000 K, respectively. For the other two lines, Doppler broadening remains dominant even for layers with larger optical depth, e.g., higher temperatures of considered atmospheric layers.

It is obvious from Figures 1–4 that Stark broadening has larger impact on Co II spectral lines in the infrared spectral range, and this impact will be larger for DB dwarfs than on the rest of the considered objects. So, we decided to investigate how effective temperature and surface gravity of DB WD affect the relationship between Stark and Doppler widths for a particular spectral line.

In Figure 5, comparison of Stark and Doppler broadening of Co II line λ9969 in white dwarf atmospheres is presented as a function of layer temperature for five different models [34] of DB white dwarf atmospheres with effective temperatures from 14,000 to 30,000 K with a step of 4000 K, and log g = 8. The effective temperature is approximately taken as the temperature of the surface of the star. As effective temperature increases, the Stark broadening becomes more prominent in layers of the DB atmosphere, with temperatures which are more and more smaller than the effective temperature, because in these layers temperature becomes high enough to ionize helium more efficiently, so that electron density is higher. For example the difference between the effective temperature and temperature where Stark and Doppler broadening are approximately equal increases from the model with T_{eff} = 14,000 K where it is several thousand kelvins to the model with T_{eff} = 30,000 K, where it is larger than 10,000 K.

Finally, in Figure 6, this comparison for the same line is shown for four model atmospheres of DB white dwarfs [34] with effective temperatures T_{eff} of 12,000 and 30,000 K, with two different values of log g for each temperature. We can see that electron-impact broadening becomes more important in DB white dwarf atmosphere than thermal broadening with the increase in surface gravity.

4. Conclusions

In this work, the usefulness and applicability of calculated set of data with Stark widths of 46 Co II lines for the investigations of spectra from atmospheres of stellar type A and hydrogen-rich (DA) and helium-rich (DB) white dwarfs are investigated. One can conclude that Stark broadening is very important for white dwarfs and for the same plasma conditions, its influence is larger for the DB than for the DA type. For A-type stars, Stark broadening may be non-negligible in comparison with thermal Doppler width, especially for higher wavelengths in the red part of the spectrum. Additionally, the influence of Stark broadening increases with the increase in the effective temperature and surface gravity analyzing as an example the DB type of WD.

We hope that the calculated set of 46 Co II Stark widths and these results will be useful for their use for hot star and WD spectroscopy, and also contribute to more accurate cobalt abundance determination. There are no other experimental or theoretical data for Stark broadening of Co II spectral lines analyzed here. As follows from our work, measurements of Stark broadening of Co II spectral lines will be of interest not only for comparison with the results obtained here but also for analysis and synthesis of stellar Co II spectral lines. This set of data, previously published as a hard copy in Ref. [3], is available online here in computer readable form. It will be implemented later and in the STARK-B database [35–38], which is also a part of the Virtual Atomic and Molecular Data Center (VAMDC) [39,40] and may be accessed through its portal [41].

Supplementary Materials: The following are available online at http://www.mdpi.com/2306-5729/5/3/74/s1, Table S1: MSE Stark Full Width at Half Intensity Maximum (WMSE) calculated for Co II transitions for five different temperature values Table S2: Coefficients for fitting formula.

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Conflicts of Interest: The authors declare no conflict of interest.

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