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L L. Cogger

Vincent B. Wickwar
Utah State University

H C. Carlson

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Combined airglow and incoherent scatter observations as a technique for studying neutral atmospheric variations

L. L. Cogger

University of Calgary, Calgary, Alberta, Canada

V. B. Wickwar

Stanford Research Institute, Menlo Park, California

H. C. Carlson

Arecibo Observatory, Arecibo, Puerto Rico[1]

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Night airglow 6300 Å intensities and electron density altitude profiles observed at Arecibo have been combined with dissociative recombination theory to obtain information about the nighttime variation of *F*-region N_2 and O_2 densities. The application of this technique is illustrated using data from two nights in March 1971. The gross nighttime variation shows reasonable similarity to the *Jacchia* [1970] model, and also follows the time variation of the measured exospheric temperature. However, on both nights there is evidence of a postmidnight enhancement of the O_2/N_2 density ratio associated with a rapid decrease in the height of the *F* layer.

INTRODUCTION

Measurements of nighttime 6300 Å airglow intensities at the Arecibo Observatory have been compared with calculations based on electron densities derived from simultaneous incoherent backscatter measurements. The good agreement found has indicated that the normal nightglow can be fully accounted for by dissociative recombination. The work leading to this conclusion, and a number of other conclusions based on it, has been partially reported by *Wickwar* [1971]. It is the purpose of the present work to use the previous findings as a basis for turning the comparison technique into a tool for studying upper atmospheric density variations.

The principle of this technique is rather simple. The 6300 Å nightglow intensity is determined not only by the altitude profiles of the ambient ion concentrations but is also sensitive to the O_2 and N_2 densities in the *F* region. Thus, if variations in the electron density and 6300 Å intensity can be accurately measured, variations in the molecular concentrations near 250 km can be inferred. Using tilting-filter 6300 Å airglow intensities and incoherent scatter electron densities, it is possible at the Arecibo Observatory to monitor neutral atmospheric density changes occurring over time scales down to a small fraction of an hour with good sensitivity.

INSTRUMENTATION

The airglow intensities were obtained with a tilting-filter photometer [*Eather and Reasoner*, 1969; *Wickwar*, 1971]. This allows accurate removal of background emissions. The effective filter bandwidth is approximately 6 Å for the 5° field of view normally used. The statistical uncertainty is approximately 5% or 5 Rayleighs, whichever is greater, and the absolute accuracy about 15% with respect to standards traceable to NBS.

The electron densities and ion temperatures were taken with the incoherent backscatter radar [*Evans*, 1969] at the Arecibo Observatory [*Gordon and LaLonde*, 1961]. The data used have nominal statistical uncertainties of 2% and 5% respectively.

[1] Presently at the University of Texas at Dallas, Dallas, Texas.

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DISSOCIATIVE RECOMBINATION CALCULATIONS

Those ionospheric atomic oxygen ions which recombine by means of the reactions:

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad (\text{rate } \gamma 1)$$

$$O_2^+ + e \rightarrow O + O \qquad (\text{rate } \alpha 1)$$

may give rise to 6300 Å airglow emission. This emission rate may be expressed as:

$$I_{6300} = 0.076 \cdot \int \{R\gamma_1 n_{O2}(h)F(h)n_e(h)/[1 + Qn_{N2}(h)/A]\}\, dh \quad (1)$$

where R = number of $O(^1D)$ excited per recombination (including cascading from $O(^1S)$)

γ_1 = the rate limiting reaction of the γ_1, α_1 pair
Q = quenching coefficient of $O(^1D)$ (the dominant collision rate is with N_2)
A = sum of Einstein coefficients for emission at 6300 and 6364 Å
F = $n(O^+)/n_e$ (and generally weakly affecting the integral)

It is convenient to rewrite this as:

$$I_{6300} = 0.076 \int \{e(h)/[1 + d(h)/A]\} n_e(h)F(h)\, dh \quad (2)$$

where $e(h) = R\gamma_1 n_{O2}(h)$ is the rate of $O(^1D)$ excitation per O^+ ion and $d(h) = Qn_{N2}(h)$ is the rate of $O(^1D)$ quenching.

Thus one may think of the 6300 Å intensity I_{6300} in terms of a product of three altitude profiles: the electron density profile times the n_{O2} profile for the excitation rate, and this excitation profile times a profile dependent on quenching (and hence n_{N2}) to give the resultant emission rate. This is illustrated in Figure 1. Note that a ground-based observation provides only the altitude integral I_{6300}.

In practice, negligible contribution to this integral comes from outside the 175 to 500 km altitude range, and most of the contribution generally comes from an altitude interval a few neutral scale heights thick centered approximately a scale height below the altitude of maximum electron density. Thus this integral depends on the values of its input parameters in the F region. The emission rate follows changes in the relevant parameters with good time resolution, since the $O(^1D)$ state lifetime is typically tens to 10^2 sec (depending on quenching).

Values of I_{6300} can be calculated using observed n_e profiles and choosing values for the constants R, γ_1, and Q as well as a model atmosphere. These calculated values can be compared with coincident observed I_{6300}. Some representative results are pre-

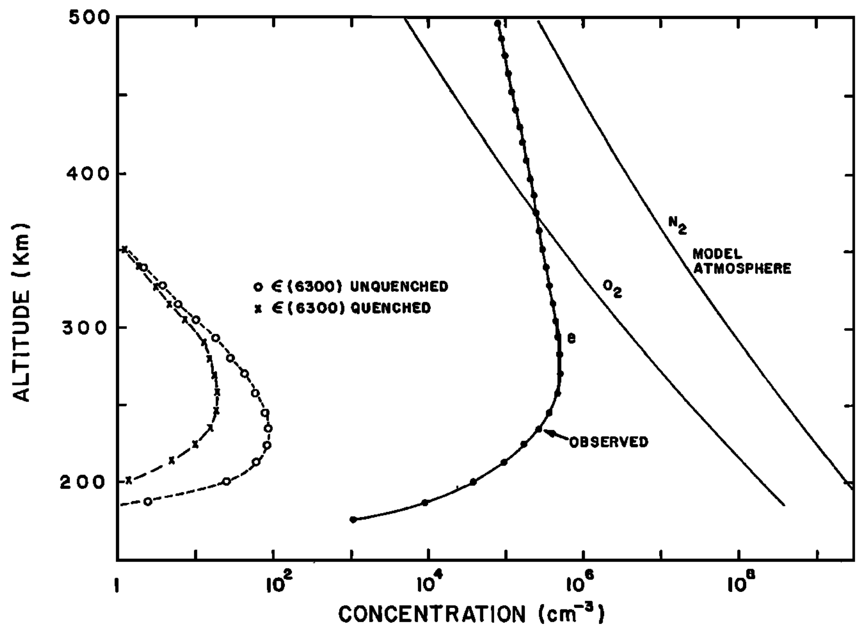

Fig. 1. Calculated volume emission rate (photons cm^{-3} sec^{-1}) of 6300 Å airglow from dissociative recombination of O_2^+ using a model atmosphere and observed electron density altitude profile. October 3, 1970 AST, Arecibo, T_∞ [*Jacchia*, 1970] = 988 K.

sented in Figures 2 and 3. *Wickwar* [1971] reports the details of some such calculations. Values of the constants may be chosen to optimize the fit for data from many nights. The agreement is generally quite good, and supports the hypothesis that the normal nighttime I_{6300} observed near Arecibo's latitude can be accounted for simply in terms of dissociative recombination.

DEDUCTION OF MOLECULAR CONCENTRATION GROSS VARIATIONS

Within the context of the above discussion, consider now how combined observations of $n_e(h)$ and I_{6300} variations allow the study of variations in n_{O2} and n_{N2} in the F region. Given $n_e(h)$ at any time, one can solve for I_{6300} assuming (temperature dependent) reaction rates, values for R and Q, and a neutral atmospheric model for n_{O2} and n_{N2}. Given a large body of data, one can fit calculated-to-observed I_{6300} by least squares to obtain best solution ranges of e and d. *Alternately,* with reference to equation 2, if one is given correct values for R, γ_1, and Q, one can solve for a weighted altitude integral dependent on $n_{O2}(h)$ and $n_{N2}(h)$. If one can only assume reasonable estimates of these three constants, one can only determine relative changes in this weighted integral.

Having chosen values for R, γ_1, and Q, and given measurements for $n_e(h)$ and I_{6300}, one is faced with the problem of how to usefully express the resultant constraint on the altitude profiles of n_{O2} and n_{N2}. Workers with satellite drag data, faced with a similar problem, have devised models leading to formulations such as the Jacchia models. It is convenient to express the findings of this dissociative recombination work in a similar context.

Recall that *Jacchia* [1970] has chosen fixed n_{O2}

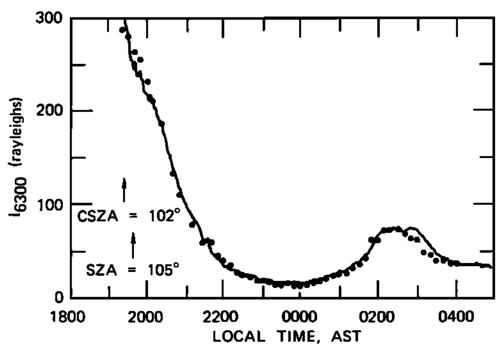

Fig. 2. Observed (—) and calculated (···) I_{6300} as a function of time for the night 26/27 March 1971, Arecibo.

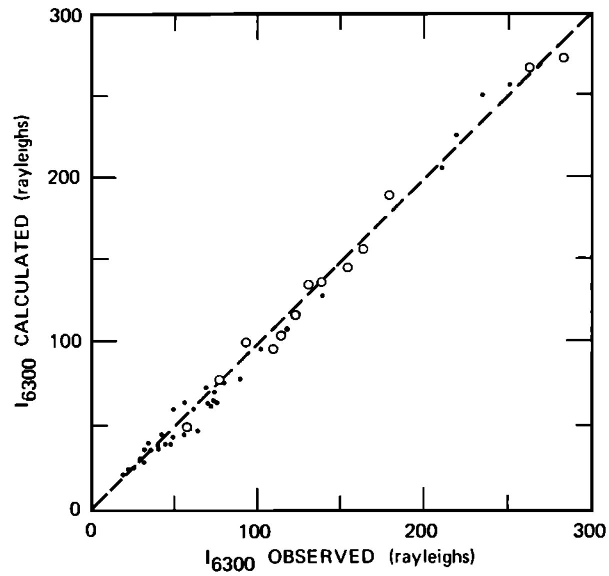

Fig. 3. Comparison of observed and calculated I_{6300} for the nights of 16/17 (○○○) and 26/27 (···) March 1971. The dashed reference line has a slope of unity.

and n_{N2} densities at a base reference altitude, and has then derived n_{O2} and n_{N2} at higher altitudes in terms of a "temperature" determined from the parameter T_∞ (similar to but not to be confused with the exospheric gas temperature). However, it is helpful to further recall that the formulation of a model atmosphere is more explicit in the Bates-Walker expression [*Walker,* 1965] which gives the profiles in terms of a density and temperature at some base reference altitude (e.g., 120 km), a T_∞ (similar to an exospheric gas temperature), and a shape parameter specifying the manner in which the "temperature" increases with altitude between its reference base value and T_∞. This formulation and terminology is of course based on the physical reasoning that, assuming that diffusive equilibrium applies above some reference altitude at which the density is known, the density at any higher altitude is expressible as a simple integral of the true temperature profile.

The molecular concentration information, obtained from the dissociative recombination calculations reported here, is thus expressed within the context of a *Jacchia* [1970] frame of reference, and in the following way. For the specific night and geophysical conditions in question, the *Jacchia* [1970] base level temperature and molecular concentrations are calculated and assumed to apply, as are the Jacchia expressions for the altitude variations of these concentrations. Fixed values for the constants R, γ_1 (temperature dependent), and Q are chosen as explained below. Then, given the observed $n_e(h)$, that value of Jacchia's T_∞ is found which makes the calculated I_{6300} equal to the observed value. The T_∞ value thus found has been designated by the symbol P_{TDR} to call attention to the fact that it is merely a parameter, similar to a temperature, which is derived to designate an F-region neutral density. Specifying the single parameters P_{TDR}, used in this model in the same way that T_∞ is used by Jacchia, thus provides a concrete and convenient definition of an F-region molecular oxygen and molecular nitrogen concentration.

The process of calculating a P_{TDR} is repeated every 5 or 10 min using consecutive n_e profiles, leading to a good time resolution variation of P_{TDR} throughout the night. The results of such calculations for the night of March 26/27, 1971 at Arecibo are shown in Figure 4. Also shown in this figure are the values of T_∞ calculated from the standard *Jacchia* [1970] model for the period in question, using appropriate values of Kp, $S10.7$, etc. These values have been designated by the symbol P_{TJ70} to call attention again to the fact that they represent a parameter (similar to a temperature) used to define the neutral density in the F region. Also shown in Figure 4 is the measured ion temperature in its near isothermal high altitude region. Since the measured ion and electron temperatures were equal (within the statistical error bars of a few percent), and no unusually large ion velocities were observed, this $\overline{T}_i$ is taken to represent the true exospheric neutral gas temperature. Prior to 01:30 $\overline{T}_i$, P_{TDR}, and P_{TJ70} all agree

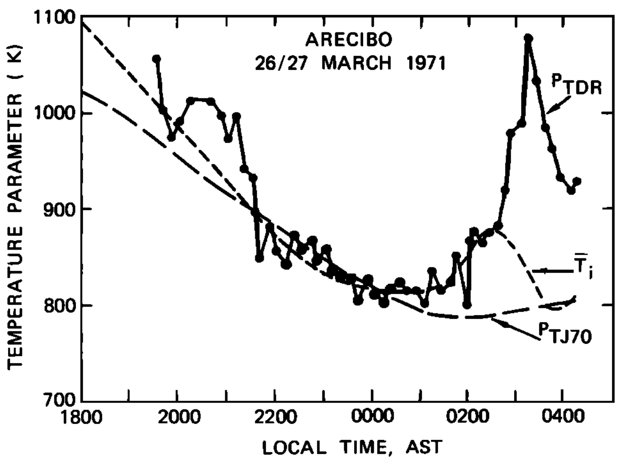

Fig. 4. Nighttime variation of F-region temperature parameters P_{TDR}, P_{TJ70}, and the observed F-region temperature $\overline{T}_i$, for 26/27 March 1971. $e(120) = 0.86$, $d(120) = 65$.

reasonably well on this magnetically quiet night, especially during the four hours centered on local midnight.

In generating these comparison curves, the uncertainty in published values of the constants $R\gamma_1$ and Q would allow a wide range of values for P_{TDR} at any one time. For the data presented here values were chosen for those constants which made P_{TDR} nearly equal to P_{TJ70} or $\overline{T}_i$ at one point in time. For the rest of the night of course these constants were held fixed, and n_e and I_{6300} were measured. Thus at all other times, the relative changes in P_{TDR} were determined by relative changes in molecular concentrations. Thus the agreement of the mean absolute value of P_{TDR} with that of P_{TJ70} or T_i is forced; it is the *relative* change with time during the night which is of significance for the work presented here. The close similarity of the time variation of P_{TJ70} and P_{TDR} is rather striking, and supports the applicability of the Jacchia model for time variations of the molecular concentrations on this night.

In going to other nights, such as in Figure 5 or 6, slightly different values of $R\gamma_1$ and Q (still within acceptable ranges on their uncertainty) would be needed to make the mean absolute value of P_{TDR} fit that of P_{TJ70} or $\overline{T}_i$. These small changes in the values assumed for the constants negligibly alter the shape of the $P_{TDR}(t)$ curve. Of course the true values of these constants do not vary from night to night (other than the weak temperature dependence of γ_1). The need to use slightly different ratios of $R\gamma_1$ to Q from one night to another (in order to make the mean P_{TDR} match that of P_{TJ70}) really reflects small night-to-night departures of true mean molecular concentrations from those predicted for any particular night by the *Jacchia* [1970] model. This will be discussed in another work. It should be noted that this fitting procedure, of calculated-to-observed I_{6300} by least squares, is quite sensitive to relative changes of the ratio n_{O2}/n_{N2}, but is relatively insensitive to the absolute molecular concentrations. As regards sensitivity, note also that a (readily detectable) 50 K perturbation enhancement of the derived parameter P_{TDR} would be produced by a perturbation enhancement of only about 5% in the true n_{O2}/n_{N2} ratio near F-region altitudes.

In Figure 5, P_{TDR} and P_{TJ70} are shown for another, but somewhat more disturbed night. The agreement is still tolerably good (prior to 03:00) though noticeably worse than in Figure 4. In Figure 6 P_{TDR} is shown together with $\overline{T}_i$ (taken to represent the exospheric neutral gas temperature). $\overline{T}_i$ is slightly lower, on the whole, than P_{TJ70} for this night. Correspondingly, slightly different values of R, γ, and Q have been chosen in Figure 6 to decrease the mean P_{TDR} to match more closely the mean $\overline{T}_i$ level. However, the time variation of P_{TDR} is essentially unchanged. In fact, the time variation of P_{TDR} (the paramater designating F-region values of n_{O2} and n_{N2} which would give the observed I_{6300}) prior to 02:45 local time agrees with that of $\overline{T}_i$ appreciably better than with that of P_{TJ70}, for both nights shown.

A plausible explanation for this could be that the Jacchia model describes the base level (and long-term mean F-region) n_{O2} and n_{N2} densities reasonably well, but over shorter time scales the F-region densities will track the exospheric gas temperature which for any particular hour or night need not match the long-term P_{TJ70}. For these nights then, the P_{TDR} (prior to 02:45) would require short term deviations (of some tens of percent) of the F-region n_{O2} and n_{N2} from the Jacchia mean model conditions, but would allow these deviations to be explained by correct Jacchia lower boundary conditions and temperature profile shapes and small (several tens of K) departures of the true exospheric temperature from the mean P_{TJ70}.

LARGE DENSITY PERTURBATIONS

Turn attenion now from the gross behavior of P_{TDR} noted above, to the rather striking perturbation starting at about 01:30 and 03:00 in Figures 4 and 6 respectively.

Each of these events is preceded by a small (about 50 K) but clear increase in $\overline{T}_i$ (taken to be the exospheric temperature). In Figure 4, during this short period of increasing $\overline{T}_i$ P_{TDR} follows $\overline{T}_i$ noticeably better than P_{TJ70}, consistent again with a correct Jacchia lower boundary and temperature profile shape, but with the need for replacing the parameter P_{TJ70} by a true exospheric temperature $\overline{T}_i$.

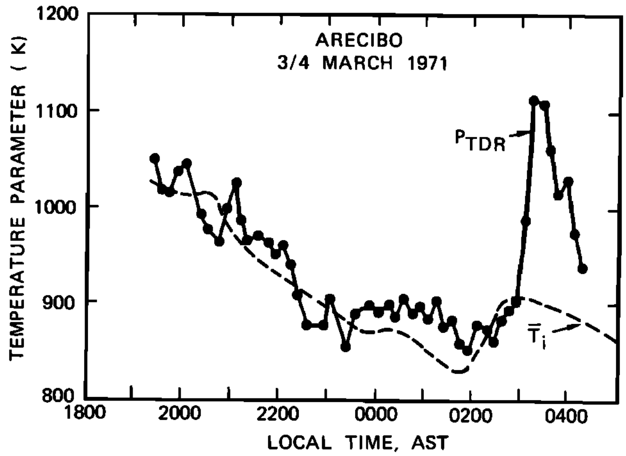

Fig. 6. Comparison of P_{TDR} and $\overline{T}_i$ for the night of 3/4 March 1971. $e(120) = 0.65$, $d(120) = 56$.

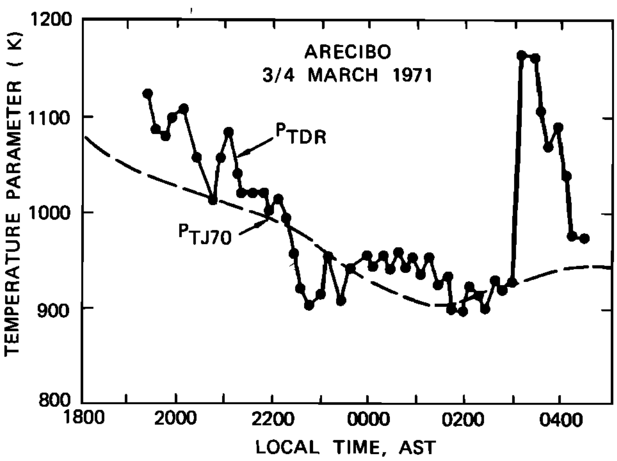

Fig. 5. Nighttime variation of F-region temperature parameters P_{TDR} and P_{TJ70} for 3/4 March 1971. Approximately, $e(120) = 0.97$, $d(120) = 80$.

The most striking effect however is the sharp departure (about 200 K) of the P_{TDR} from P_{TJ70} or $\overline{T}_i$. If P_{TDR} were simply equated to P_{TJ70}, this would imply an n_{O2} enhancement at 300 km of about a factor of two. Clearly this perturbation requires careful examination and interpretation.

This event occurs during the time of a striking F-region transport perturbation studied at some length and dubbed the "midnight descent" by *Nelson and Cogger* [1971]. The event is characterized by a rapid descent of the F region and consequent sharply enhanced recombination and I_{6300}. The event is caused by a neutral wind perturbation [*Harper,* 1971] lasting about an hour and propagating poleward from south of Arecibo. It is often seen over the 30° to 50° magnetic latitude range [*Nelson and Cogger,* 1971]. Although the source of this significant and widespread neutral wind perturbation is not yet understood, it would not be surprising to find that it was also associated with a neutral atmospheric density and composition perturbation.

The observed sharp increase in the P_{TDR} derived represents a significant F-region neutral density or composition change, since: the $n_e(h)$ is measured; the constants R, γ_1, and Q should not discontinuously change; and the γ_1 temperature dependence clearly cannot produce the observed effect. However, all that can be said with certainty is that the ratio of the F-region n_{O2}/n_{N2} has increased. A priori, this might be due to either a change in the lower boundary densities, in the neutral temperature profile shape, in the exospheric temperature, or any combination of these. The parameter P_{TDR} was used for the convenience of a concrete presentation of the findings for the earlier part of the night, and in general seems a reasonable form to hypothesize. During this strong perturbation period, however, $\bar{T}_i$ and hence presumably the true gas exospheric temperature does not show an increase. Thus it would seem rather unreasonable to suggest that the actual atmospheric departure from a Jacchia model is likely to be approximated by a Jacchia model with just the P_{TJ70} increased. It would seem much more plausible that the actual atmospheric perturbation was in a base level density or in a temperature profile shape. Clearly, during this event, the P_{TDR} plotted is purely a parameter simply defining the amount by which the ratio n_{O2}/n_{N2} is enhanced during this event. The approximately "200 K" enhancements of the derived parameter P_{TDR} would be produced by less than 20% enhancements of the F-region n_{O2}/n_{N2}.

CONCLUSIONS

Measurements of nighttime 6300 Å airglow intensities, I_{6300}, for comparison with calculations of dissociative recombination based on simultaneously observed electron density profiles $n_e(h)$, can permit study of relative changes in F-region n_{O2} and n_{N2} concentrations. The I_{6300} data must be of high accuracy, and the $n_e(h)$ must be quite accurate and extend in general over about the 175 to 450 km altitude range for optimum results. The technique should apply to low and midlatitude regions. Molecular concentration variations can be detected over time scales from a small fraction of an hour to the major part of a night. The technique has the advantage of being quite sensitive to variations in the n_{O2}/n_{N2} ratio. It has the disadvantages that: ground-based I_{6300} observations lead to smearing of $n_{O2}(h)$ and $n_{N2}(h)$ over a few neutral scale heights; and the source of the variations in n_{O2}/n_{N2} cannot be uniquely identified (e.g., variations in the base level densities, or low altitude temperature profile shape, or high altitude temperature value).

The technique has been applied to data from a few nights' observation. On these, during the normal night period, the time variation of n_{O2}/n_{N2} has been found to be consistent with that of *Jacchia* [1970], especially if one retains the Jacchia base density and profile shape but alters the high altitude temperature parameter P_{TJ70} to match an observed exospheric temperature. A significant increase in the F-region n_{O2}/n_{N2} ratio has been deduced during times of neutral wind perturbations over Arecibo. These wind perturbations are common over a large midlatitude global sector at night.

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