

NUMERICAL SIMULATION OF LIULIN-MO INSTRUMENT
FOR MEASURING COSMIC RADIATION ONBOARD
EXOMARS TRACE GAS ORBITER

Krasimir Krastev, Jordanka Semkova[#], Rositza Koleva

Received on September 4, 2023

Presented by P. Velinov, Corresponding Member of BAS, on September 26, 2023

Abstract

We present the results from numerical simulation of Liulin-MO instrument for measurement of the space radiation on board Trace Gas Orbiter (TGO) satellite of ExoMars-2016 mission during its transit to Mars in April-September 2016 [^{1,2}], using the Geant4 package. The methodology for calculating galactic cosmic rays (GCR) linear energy transfer (LET) is described. A methodology for screening false signals in the deposited energy spectra in the Liulin-MO detectors and correspondingly LET spectra is proposed. The contribution of the individual components of the spectrum of GCR in the LET spectrum is estimated. The calculated average radiation quality factor of GCR using the cleaned from false signals LET spectrum is compared with the experimental results obtained during the transit to Mars and a reasonable agreement is observed.

Key words: numerical simulation, space radiation measurements, galactic cosmic rays, linear energy transfer

Introduction. Mars is a future ambitious target for the human exploration, which will require as much as possible information and analysis about the radiation environment during the different stages of an exploratory mission. The radiation environment during the transit, on Mars and its vicinity can be very hazardous for future human exploration of the red planet. In the interplanetary space and on

[#]Corresponding author.

DOI:10.7546/CRABS.2023.11.07

Mars orbit the radiation field consists of two types of primary particles: galactic cosmic rays (GCR) and solar energetic particles (SEP) [3-5]. GCR are a permanent source of radiation hazard in the space. In the Solar system GCR flux is isotropic and their flux and spectra show a long term modulation that anti-correlates with the solar activity. The spectrum of the GCR is wide in both composition (from protons to the heaviest nuclei) and energies (from a few keV to 10^{21} eV) [6,7]. SEP are sporadic and impulsive events which result from transient solar events such as flares and coronal mass ejections (CMEs) [8,9]. Recently a CME erupted from the Sun on 28 October 2021 and was spread over such a wide area that Mars and Earth, while on opposite sides of the Sun and around 250 million kilometers apart, received an influx of energetic particles [10,11].

Interacting with the construction of the measuring instrument and its surrounding materials, the primary charged particles give rise to secondary particles whose spectrum again is wide in both composition and energy. The secondary particles generated by this interaction in turn interact with the construction of the instrument and its detector system. Thus the measured values for the flux, dose and LET spectrum of the incident charged particles need appropriate corrections regarding secondary radiation. The purpose of the present work is to justify an algorithm for calculating the LET spectrum of GCR by means of a simple system of two detectors – a telescope. The task is to obtain values for the LET spectrum of GCR, to calculate from this LET spectrum the radiation quality factor $\langle Q \rangle$, which is a measure of the biological effectiveness of the radiation, and to compare the obtained result for $\langle Q \rangle$ to the experimental values obtained during measurements in flight to Mars.

Method of measurement of LET spectra by Liulin-MO. Linear energy transfer (LET) is defined for charged particles in any medium as the quotient of dE_L divided by dl , where dE_L is the average energy locally imported to the medium by a charged particle of specific energy traversing a distance dl . dE/dx spectra in silicon can be related to LET spectra in water and the average radiation quality factor $\langle Q \rangle$ can be calculated according to the $Q(LET)$ relationship given in ICRP – 60 [12]. The LET spectrum is measured with thin semiconductor detectors, so-called ΔE detectors [13]. The flux of charged particles whose LET spectrum we measure must fall approximately perpendicular to the plane of the detector and cross it completely. To achieve these conditions, a system of semiconductor detectors, so-called telescopes, is used. Figure 1(a) shows a schematic view of Liulin-MO dosimeter box. The dosimeter Liulin-MO for measuring the radiation environment onboard the ExoMars Trace Gas Orbiter (TGO) is a module of the Fine Resolution Epithermal Neutron Detector (FREND) [14].

The detector module of the Liulin-MO instrument consists of 4 thin 300 μm thick, 20×10 mm area rectangular Si PIN photodiodes (detectors) – A, B, C and D. The parallel detectors A and B make up the AB telescope, detectors D and C make the DC telescope. The two telescopes operate independently of each other. The

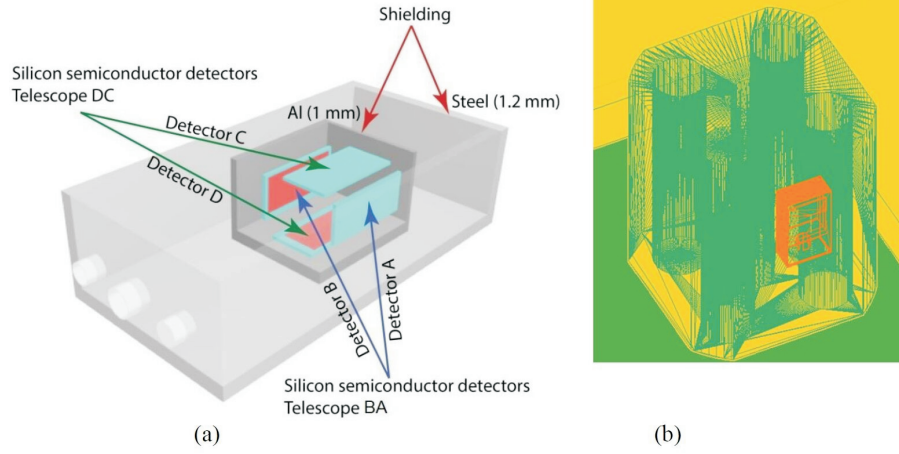


Fig. 1. (a) A schematic view of Liulin-MO detectors' location in the dosimeter box; (b) CAD model of the dosimeter Liulin-MO, FRENDO and TGO. FRENDO and TGO are in green, Liulin-MO construction is in orange lines

operation logic of the two telescopes is completely equal and the considerations we make for one apply to the other telescope as well. Each of the telescopes operates in coincidence mode. For example, a particle is detected by telescope AB if it is detected by each of detectors A and B. One of the detectors in each pair of parallel detectors measures and provides the energy deposition spectrum in the range $\sim 0.08 \div 18$ MeV. Those are detectors B and D. The other detector in each pair of parallel detectors measures the energy deposition spectrum in the range $\sim 0.3 \div 190$ MeV. Those are detectors A and C. A coincidence technique for the associated with each dosimetric telescope signals from the threshold discriminators is applied to obtain LET. The energy deposition spectra measured in A and B detectors in coincidence mode are recorded and used to obtain the LET spectrum in the direction of AB. This LET spectrum consists of low and high LET parts. The low LET part is obtained from the B coincidence spectrum in the energy deposition range $\sim 0.08 \div 15.9$ MeV and the high LET part is obtained from the A coincidence spectrum in the energy deposition range $\sim 16 \div 190$ MeV. Similarly the energy deposition spectra measured in the C and D detectors in coincidence mode are recorded separately and used to obtain the LET spectrum in the perpendicular CD direction.

Knowing the deposited energy in the detectors and their thickness we can calculate the LET.

Numerical model and simulations. The software we use is the Geant4 framework. Geant4 is a C++ language framework that is the basis for writing programs for modelling processes in high energy physics and particle physics [15]. The framework includes both ready-made models of physical processes based on experimental data and the basic theories of elementary particle physics, as well as

tools for describing own physical models. The simulation is performed using the Monte-Carlo method. The simulation takes into account the influence of electric and magnetic fields, the radioactivity of the matter. The application area of Geant4 includes particle physics and nuclear reaction research, medicine, particle accelerators, and space exploration.

The geometry is described as a gdml file. The model used is shown in Fig. 1(b). It includes the construction of TGO modelled by a plate; FRENDO – modelled as a parallelepiped and Liulin-MO.

The approach used in simulating the performance of the instrument is presented in [16,17]. For each particle and the corresponding energy from the GCR spectrum, an isotropic flux of particles with characteristics equivalent to the given particle is generated. The source of the generated particles is a sphere. The centre of the sphere coincides with the centre of the detector system of Liulin-MO. The whole geometry – TGO, FRENDO and Liulin-MO is inside the sphere. The size of the sphere is chosen for reasons of economy of the number of generated particles and therefore machine time. The distribution of the isotropic flux generated by the sphere should be cosine [13]. The time period we are looking at is the flight to Mars by the ExoMars-2016 mission in April-September 2016. The corresponding distribution for the GCR flux for this period is taken from the NASA OLTARIS database (<https://oltaris.larc.nasa.gov/>). The GCR model of Badhwar O’Neil (BON 2020) [18] is used. The number of particles that are generated for each component of the GCR spectrum is different. For protons and alpha particles 10^8 are generated, and for each of the other components 10^7 particles.

Following [17] the next formulas can be derived for the geometric factor and the count rate of the detector:

$$(1) \quad G = \frac{n}{N} 4\pi R^2.$$

Here G is the geometric factor, n is the number of registered particles from the simulation, N is the number of generated particles, R is the radius of the sphere.

$$(2) \quad C = \frac{n}{N} \pi R^2 J.$$

Here C is the detector count rate for a given GCR flux component, J is the flux for the corresponding component obtained from OLTARIS.

Results. The main results of the simulation conducted are described below. The analysis of the deposited energy by each component of GCR shows that iron Fe56 nuclei have the largest contribution in the high energy deposition range.

Figure 2 shows the correspondence between the input iron spectrum (upper plot, obtained using BON 2020 GCR model and NASA OLTARIS, and the simulated iron energy deposition spectrum in the telescope DC (bottom plot). The part of the input spectrum enclosed in the blue area and marked as cut-off energy are particles with energies that are stopped in the Liulin-MO shielding and do not

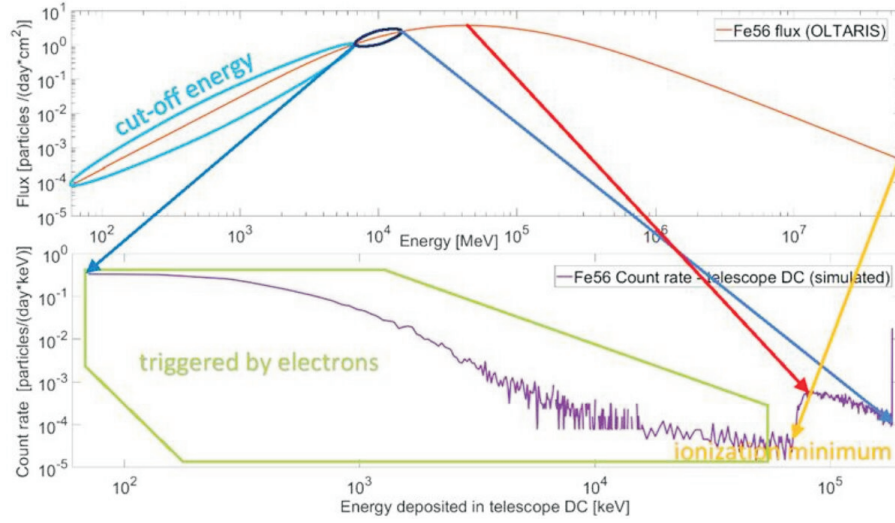


Fig. 2. Input Fe56 spectrum – top panel and output (simulated energy deposition spectrum of iron) – bottom panel

penetrate to the detectors. The marked in a small black area part of the input spectrum are particles that are stopped in one of the detectors and do not reach the other detector of the telescope. The highest energy part of the input spectrum is projected at the point around the ionization minimum^[19] in the energy deposition spectrum (see the bottom plot, where the yellow arrow shows the ionization minimum). We assume that the particles with deposited energies lower than the ionization minimum are secondary particles. The area enclosed in green on the bottom plot (called triggered by electrons) reflects cases where mainly secondary electrons are registered in each of the telescope's two detectors. The red arrow marks the maximum of the energy deposition spectrum of iron ions.

Analysis of the LET spectrum obtained from the simulation. The data shown in Fig. 2 are presented in more details in Table 1. The total flux of generated iron ions set in the simulation is 10^7 particles. With imposed trigger thresholds of 320 and 80 keV for detector A and B, respectively, 1041 events were registered. The first column of Table 1 lists all types of particles that hit the detectors A or B. The second column shows the number of hits for the corresponding particle type from column 1. The third column lists the cases in which a corresponding particle hits both detectors of the AB telescope. The fourth column represents the cases in which the corresponding particle is registered in detector A, and the fifth column gives the average energy deposited in the detector. Columns 5 and 6 represent the cases in which the corresponding particle is registered in detector B and the average energy deposited in this detector.

The detailed analysis of Table 1 shows that in the high energy range mainly iron ions are registered, and in the low energy range electrons and protons. The

T a b l e 1

Fragmentation of the spectrum for the iron ions

Type of particles	Number of registered events A or B	Number of registered events A & B	Number of registered events A	Average deposited energy per event [keV] A	Number of registered events B	Average deposited energy per event [keV] B
deuteron	44	9	29	1954	24	767
e-	407	328	368	1175	367	918
proton	165	76	138	1071	103	1210
gamma	371	223	293	0.01	301	0.01
neutron	149	64	108	0	105	0
pi+	63	13	38	345	38	492
Fe	91	8	51	114094	48	91744
alpha	18	2	10	1554	11	13601
e+	90	24	61	502	53	431
pi-	66	15	42	3756	39	310
triton	21	2	13	557	10	544
anti_nu_e	13	0	10	0	3	0
kaon+	6	0	5	1731	1	189
lambda	3	0	3	0	0	0
nu_mu	7	0	2	0	1	0
nu_e	7	0	5	0	2	0
kaon0L	3	0	3	0	0	0
pi0	1	0	1	0	0	0
He3	7	0	4	1170	3	6513
mu+	1	0	1	308	0	0
kaon0S	2	0	2	0	0	0
anti_nu_mu	2	0	2	0	0	0
kaon-	3	0	1	194	2	522

signals caused by the simultaneous registration of electrons or protons in the two detectors of the telescope are registered in the low energy deposition range and do not significantly influence the average radiation quality factor $\langle Q \rangle$.

Figure 3(a), (b) demonstrates the production of a coincidence signal. In Fig. 3(a) a heavy particle (shown in blue) passes through each of the detectors A and B of the AB telescope. This is an example of a true coincidence. Here a spurious signal is formed by the DC telescope. The detectors D and C register in coincidence mode secondary electrons and give a false coincidence. In Fig. 3(b) a heavy particle (in blue) passes through only one of the detectors (detector A) of the AB telescope, a coincidence triggered by the entry of secondary particles (in red) into detector B is registered. In this case we have a false coincidence.

Table 1 shows that the signals from Fig. 3(b) produce a major contribution to the high-energy part of the LET spectrum. A heavy particle such as an iron ion passes through detector A and deposits a relatively high energy. The secondary

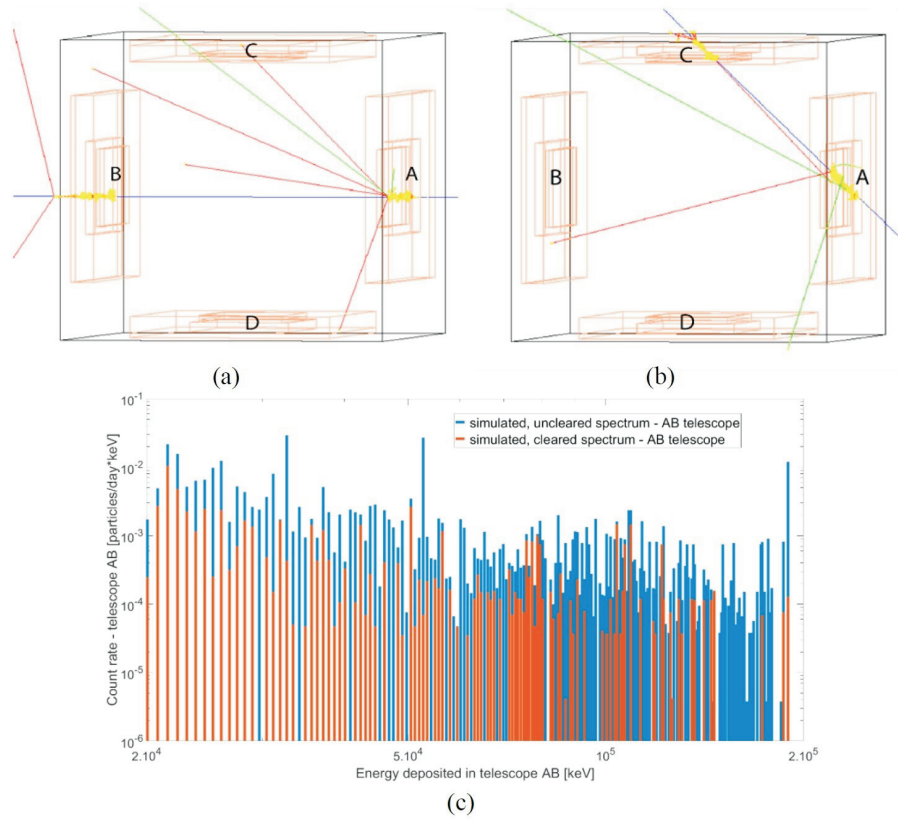


Fig. 3. True and false coincidence signals in AB telescope. (a) A heavy particle (in blue) produces a true coincidence signal; (b) A heavy particle (in blue) causes a false coincidence signal; (c) The simulated LET spectrum of iron ions. Blue lines show the LET spectrum not cleaned from false signals, the cleaned spectrum is shown in brown

electrons or protons hitting detector B give a match and a coincidence signal is registered. In this case, the signal is registered in the high-energy part of the LET spectrum and strongly affects the quality factor. Another fact that can be noted is the absence of heavy ions other than iron and alpha particles.

The above considerations allow us to ignore the cases from Fig. 3(b) and limit ourselves only to the cases from Fig. 3(a) when constructing the LET spectrum. This is the methodology by which we clear the "false" signals and build the LET spectrum.

Figure 3(c) shows the result of applying the approach described above. The algorithm is applied to each GCR spectrum component. The total spectra from the simulation are built for both cases – an uncleaned and cleaned from false signals spectra. The quality factor calculated from the cleaned LET spectrum is 3.6, which is in agreement with the experimentally obtained $\langle Q \rangle = 3.9 \pm 0.29$

by Liulin-MO dosimeter during the ExoMars transit to Mars [2], and with the value of $\langle Q \rangle = 3.82 \pm 0.28$ obtained by RAD instrument aboard of NASA MSL during its cruise to Mars [20]. The agreement is within the uncertainties of the experimental $\langle Q \rangle$ values.

Conclusion. The processes and effects that are considered in this work are not limited to the specific task. The considerations given here can be taken into account in the design of devices for measuring ionizing radiation. The results obtained from the simulation show that the physical processes that take place in the detector system and the construction of the instrument are complex and diverse. When designing the dosimetric device to eliminate unwanted effects, in most cases various clever methods are applied, but this does not always lead to the desired accuracy. In many cases, numerical modelling turns out to be the only way to assess the influence of a given factor. The Geant4 package is constantly being upgraded based on experiment and theory, but the results achieved based on the current versions are very satisfactory.

The present work shows that secondary protons and electrons are the main culprits for the distortion of the LET spectrum, and a quantitative assessment of this unwanted effect is also made. Deuterons and alpha particles also make a significant contribution, while the contribution of other particles can be neglected. The results of the simulation show a good agreement with the experiment, which largely proves the correctness of the methodology used here.

REFERENCES

- [1] SEMKOVA J., T. DACHEV, ST. MALTCHIEV, B. TOMOV, YU. MATVIICHUK et al. (2015) Radiation environment investigations during ExoMars mission to Mars – objectives, experiments and instrumentation, *C. R. Acad. Bulg. Sci.*, **68**(4), 485–496.
- [2] SEMKOVA J., R. KOLEVA, V. BENGHIN, T. DACHEV, YU. MATVIICHUK et al. (2018) Charged particles radiation measurements with Liulin-MO dosimeter of FRENDA instrument aboard ExoMars Trace Gas Orbiter during the transit and in high elliptic Mars orbit, *Icarus*, **303**, 53–66.
- [3] MIROSHNICHENKO L. I., V. M. PETROV (1985) In: Dynamics of the radiation conditions in space, M:Energoatomizdat, 152 (in Russian).
- [4] CUCINOTTA F. A., S. HU, N. A. SCHWADRON, K. KOZAREV, L. W. TOWNSEND et al. (2010) Space radiation risk limits and Earth–Moon–Mars environmental models, *Space Weather*, **8**(12), doi: 10.1029/2010SW000572.
- [5] DURANTE M., F. A. CUCINOTTA (2011) Physical basis of radiation protection in space travel, *Rev. Mod. Phys.*, **83**(4), 1245–1281.
- [6] VELINOV P. I. Y. (1966) An expression for ionospheric electron production rate by cosmic rays, *C. R. Acad. Bulg. Sci.*, **19**(2), 109–112.
- [7] USOSKIN I., L. DESORGHER (2009) Ionization of the Earth’s atmosphere by solar and galactic cosmic rays, *Acta Geophys.*, **57**(1), 88–101.

- [8] REAMES D. V. (2013) The Two Sources of Solar Energetic Particles, *Space Sci. Rev.*, **175**, 53–92, <https://doi.org/10.1007/s11214-013-9958-9>.
- [9] VELINOV P. I. Y., S. ASENOVSKI, K. KUDELA, J. LASTOVICKA, L. MATEEV et al. (2013) Impact of cosmic rays and solar energetic particles on the Earth's ionosphere and atmosphere, *J. Space Weath. Space Clim.*, **3**, A14, 1–17, <https://doi.org/10.1051/swsc/2013036>.
- [10] GUO J. X. LI, J. ZHANG, M. I. DOBYNDE, Y. WANG et al. (2023) The First Ground Level Enhancement Seen on Three Planetary Surfaces: Earth, Moon, and Mars, *Geophys. Res. Lett.*, **50**(15), e2023GL103069, <https://doi.org/10.1029/2023GL103069>.
- [11] VELINOV P. (2022) Major X-Class Solar Flare from Earth-Facing Active Region AR12887 on October 28, 2021 and First Cosmic Ray GLE 73 in Solar Cycle 25, *C. R. Acad. Bulg. Sci.*, **75**(2), 248–258.
- [12] Space exploration (1990) Academy of Sciences [AS] USSR, T.32, Instruments and methods for recording cosmic radiation, (eds P. V. Shcheglov, A. P. Kropotkin) p. 185.
- [13] ICRP (1991), Report No. 60, Pergamon Press, Oxford.
- [14] MITROFANOV I., A. MALAKHOV, B. BAKHTIN, D. GOLOVIN, A. KOZYREV et al. (2018) Fine Resolution Epithermal Neutron Detector (FREND) onboard the Exo-Mars Trace Gas Orbiter, *Space Sci. Rev.*, **214**(86), <https://doi.org/10.1007/s11214-018-0522-5>.
- [15] AGOSTINELLI S., J. ALLISON, K. AMAKO, J. APOSTOLAKIS, H. ARAUJO et al. (2003) Geant4 – a simulation toolkit, *Nucl. instruments methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, **506**(3), 250–303.
- [16] ZHAO X.-Y., H.-Y. WANG, F. WU, X.-C. MENG, Y.-Q. MA et al. (2013) A Geometric Factor Calculation Method Based on the Isotropic Flux Assumption, *China Physics C*, **37**(12), 126201.
- [17] PAK S., Y. SHIN, J. WOO, J. SEON (2018) A numerical method to analyze geometric factors of a space particle detector relative to omnidirectional proton and electron fluxes, *J. Korean Astron. Soc.*, **51**(4), 111–117.
- [18] O'NEILL P., S. GOLGE, T. C. SLABA (2015) Badhwar–O'Neill 2014 galactic cosmic ray flux model description, NASA/TP-2015-218569, Retrieved from <https://ntrs.nasa.gov/citations/20150003026>.
- [19] EIDELMAN S., K. G. HAYES, K. A. OLIVE, M. AGUILAR-BENITEZ, C. AMSLER et al. (2004) Review of Particle Physics, *Phys. Lett., B*, **592**(1–4), 1–5.
- [20] ZEITLIN C., D. M. HASSLER, F. A. CUCINOTTA, B. EHRESMANN, R. F. WIMMER-SCHWEINGRUBER et al. (2013) Measurements of Energetic Particle Radiation in Transit to Mars on the Mars Science Laboratory, *Science*, **340**(6136), 1080–1084.

*Space Research and Technology Institute
Bulgarian Academy of Sciences
Akad. G. Bonchev St, Bl. 1
Sofia 1113, Bulgaria*

e-mail: werholak@abv.bg
jsemkova@stil.bas.bg, jordankasemkova@gmail.com
rkoleva1900@gmail.com